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ACRONYMS, ABBREVIATIONS AND SYMBOLS

\AA :	Angstrom Unit
A:	Ampere
AAP:	Apollo Applications Program
ABC:	American Broadcasting Company
ac:	Alternating Current
accum:	Accumulator
accomp:	Accomplishment
acquis:	Acquisition
Acq. SS:	Acquisition Sun Sensor
ACS:	Attitude Control System
A-D:	Analog-to-Digital
ADDT:	All Digital Data Tape
ADP:	Acceptance Data Package
ADRS:	Automated Data Requirements System
AES:	Apollo Extension System
AFETRM:	Air Force Eastern Test Range Safety Manual
AFO:	Announcement of Flight Opportunity
AGC:	Automatic Gain Control
AGE:	Aerospace Ground Equipment
A-h:	Ampere-hour(s)
AHI:	Ampere Hour Integrator
A-hm:	Ampere hour meter
α s:	Solar Absortivity
ALC:	Audio Load Compensator
Al:	Aluminum
AM:	Airlock Module/Amplitude Modulation
AMS:	Airlock Module Station/Articulated Mirror System
Ang:	Angular
APCS:	Attitude Pointing and Control Subsystem
AR:	Action Request
ARIA:	Apollo Range Instrumentation Aircraft
ASA:	Amplifier and Switching Assembly
ASAP:	Auxiliary Storage and Playback Assembly
ASC:	Administration Support Center
AS&E:	American Science and Engineering
ASP:	Activity Scheduling Program
AST:	All Systems Test
ASTN:	Astronautics Laboratory
ASTR:	Astronics Laboratory
ATM:	Apollo Telescope Mount
ATMCC:	Apollo Telescope Mount Control Computer
ATM/DA:	Apollo Telescope Mount Deployment Assembly
ATMDC:	ATM Digital Computer
ATOM:	Apollo Telescope Optical Mount
ATP:	Acceptance Test Procedure
ATT:	Attitude
AUX:	Auxiliary
AVE:	Aerospace Vehicle Equipment
AVG:	Average
AVO:	Avoid Verbal Order
AWG:	American Wire Gauge

β : Beta Angle
 β/β_0 : Scattered Light Brightness Ratio
 batt: Battery
 BC: Backup Components
 BED: Box External Data
 BID: Box Internal Data
 BI-LCA: Backup Inverter-Lighting Control Assembly
 BIOMED: Biomedical
 BOM: Beginning of Mission
 bps: Bits per second
 brkr: Breaker
 BSE: Booster Systems Engineer
 Btu: British Thermal Unit
 BZT: Benzotriazole

 C: Centigrade
 CAPAC: Capacity
 CARR: Customer Acceptance Readiness Review
 CB: Circuit Breaker
 CBRM: Charger/Battery/Regulator Module
 CBS: Columbia Broadcasting Company
 CC: Control Computer
 CCB: Configuration Control Board
 CCBD: Configuration Control Board Directives
 CCSR: Crew Compartment Stowage Review
 CCU: Crewman Communication Umbilical
 CCWG: Contamination Control Working Group
 C&D: Control(s) and Display(s)
 Cd: Cadmium
 CDDT: Countdown Demonstration Test
 CDR: Critical Design Review
 CE: Console Engineer
 CEI: Contract End Item
 C²F²: Crew Compartment Fit and Function
 CFE: Contractor Furnished Equipment
 cfm: cubic feet per minute
 CHA: Channel
 CHS: Conical Horizon Sensor
 CHX: Condensing Heat Exchanger
 CI: Configuration Inspection
 CIL: Critical Items List
 CIR: Configuration Inspection Review
 cir: circuit
 CIWG: Change Integration Working Group
 CLO: Clothing Resistance
 CLOUD: Cloud Math Model
 Cm: Carrier Margins
 cm: centimeter
 CM: Command Module/Configuration Management
 CMA: Configuration Management Accounting
 CMG: Control Moment Gyro
 CMGEA: Control Moment Gyro Electronics Assembly
 CMGIA: Control Moment Gyro Inverter Assembly
 CMSG: Contamination Mission Support Group

CNST: Canister
 CNTL: Control
 CO₂: Carbon Dioxide
 COAX: Coaxial
 COFW: Certification of Flight Worthiness
 COCOA: Computer Oriented Communications Operational
 Analysis
 Compt: Compartment
 COND: Condensor
 Cond: Conditioned
 CONF: Conference
 CONT: Continued
 COORD: Coordination
 CPCB: Crew Procedures Change Board
 CPDS: Crew Procedures Data System
 CPU: Central Processing Unit
 CR: Change Request/Critical Redundant
 CRB: Change Review Board
 CRBC: Critical Redundant Backup Component
 CRDU: Command Relay Driver Unit
 CRT: Cathode Ray Tube
 CRS: Cluster Requirements Specification
 CSA: Control Switching Assembly
 CSDR: Cluster Systems Design Review
 CSM: Command and Service Module
 CSR: Crew Station Review
 CTCV: Chiller Thermal Control Valve
 C&W: Caution and Warning
 CWA: Conference Work Area
 CWU: Caution and Warning Unit
 CYRO Cryogenic

 DA: Deployment Assembly/Data Acquisition
 DAC: Data Acquisition Camera
 DAR: Data Acquisition Room
 DAS: Digital Address System
 DASS: Data Acquisition Statusing System
 dB: decibel
 dBi: decibel isotropic
 dc: direct current
 DCCL: Data Core Coordination Line
 DCR: Design Certification Review
 DCS: Digital Command System
 DDC: Data Dissemination Clerk
 DDR: Data Dissemination Room
 DECOM: Decommutator
 deg: Degrees
 DEMOD: Demodulation
 DEN: Denver
 DEV: Development
 dia: Diameter
 Diplxr: Diplexer
 DIR: Director
 DISP: Display
 DMR: Data Management Room

DN: Down
 DOD: Department of Defense/Depth of Discharge
 DOY: Day-of-Year
 DP: Development and Payloads
 DR: Discrepancy Report
 DRC: Data Requirements Coordinator
 DRF: Data Request Form
 DRM: Data Requirements Manager
 DRP: Data Requirements Processor
 DS: Display Specialist
 DSO: Data Support Organization
 DTA: Dynamic Test Article
 DTO: Detailed Test Objective
 D/TV: Digital to Television
 DVTU: Design Verification Test Units
 dwg: Drawing
 DWS: Dry Workshop

ε: Emissivity
 ECE: Experiment Checkout Equipment
 ECP: Contractor Engineering Change Request
 ECR: Engineering Change Request
 ECS: Environmental Control System
 ED: Experiment Developer
 EDC: Experiment Development Center
 EDCR: Engineering Design Change Request (JSC)
 EDT: Eastern Daylight Time
 EI: Experiment Integration
 EIC: Experiment Integration Center
 EIP: Experiment Implementation Plan
 EIRD: Experiment Integration Requirements Document
 EITRS: Experiment Integration Test Requirements and Specification

EL: Electroluminescent Lighting
 elec: electrical
 EMC: Electromagnetic Compatibility
 Emerg: Emergency
 EMI: Electromagnetic Interference
 eng: engineering
 enviro: environmental
 EOM: End of Mission
 EPCS: Experiment Pointing Control Subsystem
 EPDS: Electrical Power Distribution System
 EPEA: Experiment Pointing Electronics Assembly
 EPS: Electrical Power System/Experiment Pointing System
 ERD: Experiment Requirements Document
 EREP: Earth Resources Experiments Package
 ESE: Electrical Support Equipment
 ESS: Experiment Support System
 E/TCS: Environmental/Thermal Control Subsystem
 EVA: Extravehicular Activity
 exp: Experiment
 EXT: Extension

F: Fahrenheit
 FAS: Fixed Airlock Shroud
 FCE: Flight Crew Equipment
 FDIR: Flight Director (Flight Control Position)
 FEC: Field Engineering Change
 FFEA: Functional Failure Effect Analysis
 FLEX: Flexible
 FM: Frequency Modulation/Facility Manager/Flow Meter
 FMEA: Failure Modes and Effects Analysis
 FMS: Food Management System
 FO: Functional Objective
 FOMR: Flight Operations Management Room
 FRR: Flight Readiness Review
 FRT: Flight Readiness Test
 FSA: Fire Sensor Assembly
 FSCP: Fire Sensor Control Panel
 FSS: Fine Sun Sensor
 FTS: Functional Test Specification/Federal Telecommuni-
 cation System
 FWD: Forward
 FY: Fiscal Year

G: Gaseous
 g: gravity/grams
 g/cm²: grams per square centimeter
 GE: General Electric Company
 gen: generator
 GFE: Government Furnished Equipment
 GFP: Government Furnished Property
 GG: Gravity Gradient
 gms/cm²/HR: Grams per square centimeter per hour
 GMT: Greenwich Mean Time
 GN₂: Gaseous Nitrogen
 GOSS: Ground Operational Support System
 GRA: Gimbal Ring Assembly
 grnd: ground
 GS: Ground Support
 GSFC: Goddard Space Flight Center
 GSE: Ground Support Equipment
 GSI: Government Source Inspection
 gyro: gyroscope

H₂: Hydrogen
 H- α : Hydrogen Alpha
 hdwr: hardware
 HFMU: High Fidelity Mockup Unit
 Hg: Mercury
 HIR: Hardware Integrity Review
 HLAA: High Level Audio Amplifier
 H₂O: Water
 HOSC: Huntsville Operations Support Center
 HPI: High Performance Insulation

Hq: Headquarters
 hrs: hours
 H₂S: Hydrogen Sulfide
 HSL: Hardware Simulation Laboratory
 Htr: Heater
 HX: Cabin Heat Exchanger
 Hz: Hertz

 I: Iodine
 IBM: International Business Machine Corporation
 I&C: Instrumentation and Communication
 ICA: Information Correlator Assembly
 ICD: Interface Control Document
 ICR: Information Control Room
 IDR: Interface Discrepancy Report
 IEU: Interface Electronic Unit
 IFM: Inflight Maintenance
 I/LCA: Inverter/Lighting Control Assembly
 init: initiate
 int: internal
 integ: integrated
 IOA: Input/Output Assembly
 IP&CL: Instrumentation Program and Components List
 IRN: Interface Revision Notice
 ISR: Incremental Summary Review
 IU: Instrument Unit
 IVA: Intravehicular Activity

 JSC: Johnson Space Center

 k: Thousand/Kilo
 K: Kelvin
 K₂HPO₄: Dipotassium Hydrogen Phosphate
 KHz: Kilohertz
 KMI: Kennedy Management Instructions
 KSC: Kennedy Space Center, Florida
 kV: Kilovolts

 L: Left
 lb: pound
 LC: Launch Complex
 LCC: Launch Critical Component
 LCG: Liquid Cooled Garment
 LDX: Long Distance Exchange
 LEM: Lunar Explorer Module
 LES: Launch Escape System
 LH₂: Liquid Hydrogen
 LHCP: Left-hand Circular Polarization
 LIEF: Launch Information Exchange Facility
 LiOH: Lithium Hydroxide
 LM: Lunar Module
 LM&SS: Lunar Mapping and Scientific Survey
 loc: Location
 LOX: Liquid Oxygen
 LT: Light

LWCCU: Light Weight Crewman Communication Umbilical
 LWHS: Light Weight Headset
 LV: Launch Vehicle
 LVDC: Launch Vehicle Digital Computer

 MAEB: Materials Application Review Board
 maint: maintenance
 malf: malfunction
 MAN: Management
 MAR: Mission Action Request
 max: maximum
 MCC: Mission Control Center
 MCR: Main Conference Room
 MCS: Mission Control Center Configuration Supervisor
 MDA: Multiple Docking Adapter
 MDAC-ED: McDonnell Douglas Astronautics Company-Eastern
 Division
 MDAC-WD: McDonnell Douglas Astronautics Company-Western
 Division
 MDRS: Mission Data Retrieval System
 mech: Mechanical
 MER: Mission Evaluation Room
 met: metabolic
 MGMT: Management/Manager
 mgr: Manager
 MHz: Megahertz
 MIB: Minimum Impulse Bit
 MIL: Military Specification
 min: minimum/minute
 MLFMEA: Mission Level Failure Modes and Effects Analysis
 MLU: Memory Loading Unit
 mm: millimeter
 MMC: Martin Marietta Aerospace
 MMH: Monomethylhydrazine
 MMI: Marshall Management Instructions
 mo: month
 MOC: Mission Operations Computer
 MOCR: Mission Operations Control Room
 mod: modulation/modification
 mon: monitor
 MOPS: Mission Operations Planning System
 MPC: Manual Pointing Controller
 MRB: Material Review Board
 MRD: Mission Requirements Document
 MRR: Mission Requirements Review Room
 ms: millisecond
 MSC: Manned Spacecraft Center
 MSCM: Manned Spacecraft Criteria Manual
 MSFC: Marshall Space Flight Center
 MSFEB: Manned Space Flight Experiments Board
 MSFTP: Manned Space Flight Telemetry Processor
 MSG: Mission Support Group
 MSGL: Mission Support Group Leader

MSLR: Marshall Skylab Representative
 MSN: Manned Space Network
 MSOB: Manned Space Operations Building
 MTRAP: Martin Thermal Radiation Analyzer Program
 MT/ST: Magnetic Tape Selectric Typewriter
 multi: Multiple
 mV: millivolts

N: Newton
 N₂: Nitrogen
 N/A: Not Applicable/Not Available
 NAR: North American Rockwell
 NASA: National Aeronautics and Space Administration
 NB: Neutral Buoyancy
 NBC: National Broadcasting Company
 NBS: Neutral Buoyancy Simulator
 NH₃: Ammonia
 NHB: NASA Handbook
 Ni: Nickel
 N/m²: Newton/square meter
 n mi: Nautical Miles
 NMI: NASA Instructions
 nom: nominal
 NPV: Nonpropulsive Vent
 NRZ: Nonreturn to zero
 ntwk: network

O₂: Oxygen
 O₄: Tetroxide
 OA: Orbital Assembly
 OAT: Operational Acceptance Test
 O&C: Operations and Checkout Building
 OCV: Open Circuit Voltage
 OD: Operations Director
 ODB: Operations Data Book
 ODG: Operations Data Group
 ODRAP: Deposition Math Model
 OECO: Outboard Engines Cutoff
 OIS: Operational Intercom System
 omni: omindirectional
 OMP: Online Math Processor
 OMR: Operations Management Room
 OMSF: Office of Manned Space Flight
 OSM: Operations Support Manager
 OSR: Operations Support Room
 OVBD: Overboard Dump
 OWS: Orbital Workshop

P: Pressure
 PA: Payload Assembly
 PABX: Private Automatic Branch Exchange
 PAD: Pre-Advisory Data
 PAM: Pulse Amplitude Modulation
 PAO: Public Affairs Office
 PATRS: Post Acceptance Test Requirements Specification

P/B: Playback
 PCG: Power Conditioning Group
 PCM: Pulse-Code Modulation
 PCN: Program Control Number
 PCR: Procedure Change Request
 PCS: Pointing Control System/Power Conditioning System
 PCSA: Pointing Control System Assembly
 PCU: Pressure Control Unit
 PDR: Preliminary Design Review
 PDTR: Predelivery Turnover Review
 perf: perforation
 PERT: Program Evaluation Review Technique
 PI: Principal Investigator
 PIA: Preinstallation Acceptance
 PLV: Postlanding Ventilation
 PM: Phase Modulation
 P/N: Property Number
 PNL: Panel
 POS: Position
 PP/pp: Partial Pressure
 ppm: parts per million
 pps: pulses per second
 PR: Pressure Relief
 prep: preparation
 press: pressure
 prim: primary
 prog: program
 prop: propulsion
 PRR: Preliminary Requirements Review
 PS: Payload Shroud/Pressure Switch
 psi: pounds per square inch
 psia: pounds per square inch absolute
 psid: pounds per square inch differential
 psig: pounds per square inch gage
 PSK: Phase Shift Keyed
 PSRD: Program Support Requirements Document
 PU: Propellant Utilization
 PWM: Pulse Width Monitor
 pwr: power

 q: heat flow rate
 QCM: Quartz Crystal Microbalance-Contamination Sensor
 QD: Quick Disconnect
 Q/L: Quick Look
 QLDS: Quick Look Data System
 qtrs: Quarters
 qual: qualification/quality

 R: Right/Relief Valve
 rad: radian
 RASM: Remote Analog Submultiplexer
 RBPV: Radiator Bypass Valve
 RCA: Radio Corporation of America
 RCP: Roll Control Panel
 RCS: Reaction Control System

rcvr: receiver
rec: record
Reg: Regulator/Regulated
regen: regenerator/regenerative
REPRESS: Repressurization
reqmt: requirement(s)
Resv: Reservoir
RF: Radio Frequency
RFI: Radio Frequency Interference
RH: Relative Humidity
RHCP: Right Hand Circular Polarization
RID: Review Item Discrepancy
RM: Resupply Module
rms: root mean square
RNB: Radio Noise Burst Monitor
RPM: Roll Positioning Mechanism
RS: Refrigeration System
RSCC: Remote Site Computer Complex
RSDP: Remote Site Data Processor
RT: Real Time
RTTA: Range Tone Transfer Assembly
RZ: Return to zero

S-: Saturn Stage (Prefix)
S: Liquid/Gas Separator
SA: Solar Array
SAA: South Atlantic Anomaly
SAC: Support Action Center
SAG: Solar Array Group
SAL: Scientific Airlock
SAM: Solar Array Module
SAR: Spacecraft Acceptance Review
SARP: Schedules and Resources Summary
SAS: Solar Array System
S/C: Spacecraft
SC: Signal Conditioning
SCAM: Simplified Cluster Atmosphere Model
SCD: Specification Control Drawing
SCGTP: Skylab Contamination Ground Test Program
SCIB: Spacecraft Implementation Board
SCIT: Standard Change Integration and Tracking
SCPS: Skylab Cluster Power Simulator
SCR: Sneak Circuit Review
S&E: Science and Engineering
sec: Secondary/Second
SE&I: Systems Engineering and Integration
SEL: Systems Engineering Laboratories
SF: Subframe
SFP: Single Failure Point
SI: Solar Inertial
SIA: Speaker Intercom Assembly
sig: signal
SL: Skylab

TMF: Torque Measuring Fixture
 TMR: Triple Modular Redundant
 TNK: Tank
 TNT: Tri-Nitro Toluene
 TPF: Rendezvous Terminal-Phase Finalization Maneuver
 TPI: Rendezvous Terminal-Phase Initiation Maneuver
 TQ: Test and Quality
 Tr: time-to-go to Command System Transfer (Airlock Module Timer)/Tape Recorder
 TRS: Time Reference System
 TSU: Thermal Systems Unit
 TV: Television
 Tx: time-to-to to Equipment Reset (Airlock Module Timer)
 typ: typical

UA: Heat Transfer Coefficient
 UHF: Ultrahigh Frequency
 USB: Unified S-Band
 UV: Ultraviolet
 UXM: Universal Extension Mechanism

V: Volts
 VAB: Vertical Assembly Building
 VATF: Vibro Acoustic Test Fixture
 Vdc: Volts direct current
 vel: velocity
 verif: verification
 vib: vibration
 VHF: Very High Frequency
 VR: Viewing Room
 VSWR: Voltage Standing Wave Ratio
 VTR: Video Tape Recorder
 VTS: Viewfinder Tracking System

W: Watt
 WACS: Workshop Attitude Control System
 WAR ROOM: Problem Resolving Room
 WCIU: Workshop Computer Interface Unit
 WLC: White Light Coronagraph
 WMC: Waste Management Compartment
 WMS: Waste Management System
 WPS: WACS Propulsion System
 WS: Workshop
 WSTF: White Sands Test Facility
 WWS: Wet Workshop

X-IOP: X-axis in the Orbit Plane
 XMTR: Transmitter
 X-POP: X-axis Perpendicular to the Orbital Plane
 X-Ray: X-Ray Systems
 X-REA: X-Ray Event Analyzer
 XUV: Extreme Ultraviolet

SL-: Skylab Mission (Prefix)
 SLA: Spacecraft Lunar Module Adapter
 SLCN: Stowage List Change Notice
 SL-EI: Systems Engineering and Integration Office
 SL-DP: Experiment Development and Payload Evaluation
 Project Office
 SL-R: Skylab Rescue Mission
 SL-SE-ATM: ATM Project Office
 SL-TQ: Test, Reliability, Quality Assurance, and Safety Office
 SLV: Saturn Launch Vehicle
 SLVR: Saturn Launch Vehicle Representative
 SM: Service Module
 SMEAT: Skylab Medical Experiments Altitude Test
 S/N: Serial Number
 SOC: State of Charge
 SOCAR: Skylab Systems Operations Compatibility Assessment
 Review
 SPC: Support Coordinator
 Spec: Specification
 SPG: Single Point Ground
 SPR: Sponsoring Program Offices
 SPS: Service Propulsion System
 SRPR: Systems Report Preparation Room
 SSES: Spent Stage Experiment Support Modules
 SSR: Staff Support Room
 STA: Static Test Article/Station
 STDN: Space Flight Tracking and Data Network
 str: structures
 STS: Structural Transition Section/Skylab Terminal System
 STU: Skylab Test Unit
 SUS: Suit Umbilical System
 SV: Sieve
 SW: Switch/Saturn Workshop
 SWS: Saturn Workshop
 sync: synchronous
 SYS: System

 T: Temperature Sensor
 TACS: Thruster Attitude Control System
 TAR: Target Analysis Room
 TBC: The Boeing Company
 TBD: To Be Determined
 TBS: To Be Supplied
 TCB: Time Correlation Buffer
 TCN: Test Change Notice
 TCOP: Test and Checkout Plan
 TCP: Test and Checkout Procedure
 TCRSD: Test and Checkout Requirements Specification Document
 TCS: Thermal Control System
 TCV: Temperature Control Valve
 TELE: Telescope
 T/Temp/TEMP: Temperature
 Tele: Telephone
 THERM: Thermal
 TM/TLM: Telemetry

Z-LV: Z-axis Parallel to Local Vertical
Z-LV(E): Z-axis Parallel to Local Vertical (EREP Passes)
Z-LV(R): Z-axis Parallel to Local Vertical (Rendezvous Mode)
ZOP: Zero Order Predictor

I. Program Engineering and Integration Summary

SECTION I. PROGRAM ENGINEERING AND INTEGRATION SUMMARY

A. Introduction

The Skylab program achieved a major step in the development of the nation's manned space technology. The Skylab workshop, shown in Figure I.A-1 represents the first multidisciplined laboratory in a space program to provide capabilities for solar and stellar astronomy, space physics, materials processing, biomedical evaluation and investigation of space technology. This spectrum of scientific applications and technology development activity was conducted and controlled by three-man crews. In terms of the breadth of experimentation and the quantity and quality of data, the efficiency of Skylab was considered excellent.

Man was the key to this efficiency. Through his efforts failure of potential catastrophic proportions, the loss of the meteoroid protection panel during the first minute after launch, was overcome. The failure resulted in the loss of one electrical power generating solar panel, ability to fully extend another, and the loss of solar thermal protection for the Orbital Workshop (OWS) habitation area. A solar sun shade parasol furnished by the Johnson Space Center (JSC) was erected, the remaining solar panel was extended and the nominal mission plan regained. Ultimately, a second solar sun shade furnished by the Marshall Space Flight Center (MSFC) was erected and utilized throughout the remainder of the Skylab mission for OWS thermal protection. Figure I.A-2 depicts the final operational configuration of Skylab.

Also, through crewmember efforts, diverse experiments were activated from their protected launch stowage condition. The crew was able to operate this varied complement of experiments throughout the flight and meet the desired objectives. Judgement played a critical role in the conduct of key experiments through recognition of important transient events such as solar flares and local environmental conditions. The crew adapted to the orbital environment, and then demonstrated man's ability to exploit it, permitting the durations of the second and third visits to be extended to 59 days and 84 days from the initially planned 56 days.

The Skylab missions demonstrated the teamwork concept on the part of multi-organizations with diverse interests. Investigation of the comet Kohoutek during the third visit demonstrated an ability to introduce in "real time" into an ongoing mission, observations of a comet which was not part of the original mission planning. This flexibility is a credit to the Skylab crews, mission operations and support personnel, equipment design and the Scientific Community.

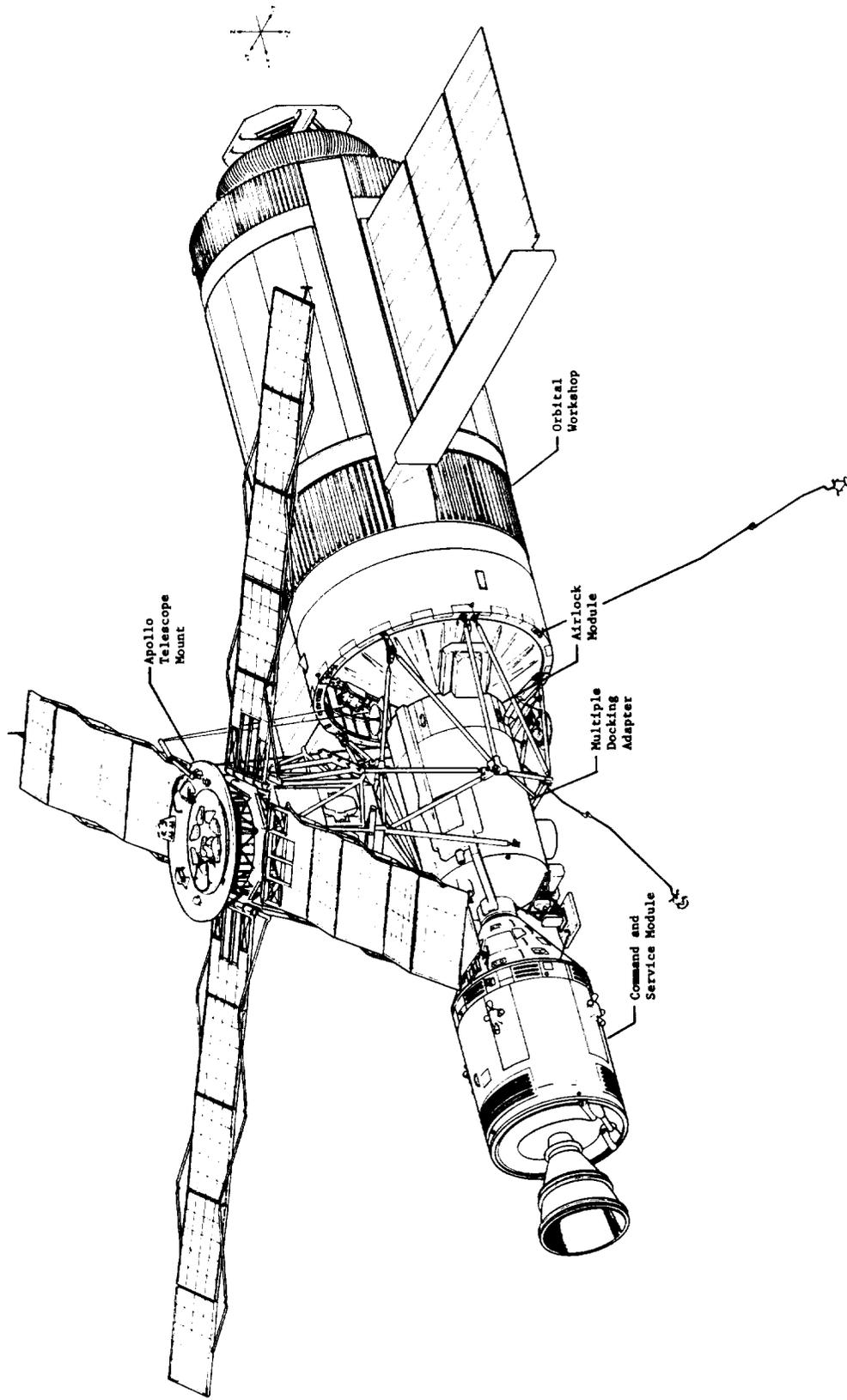


Figure I.A-1 Skylab Orbital Assembly

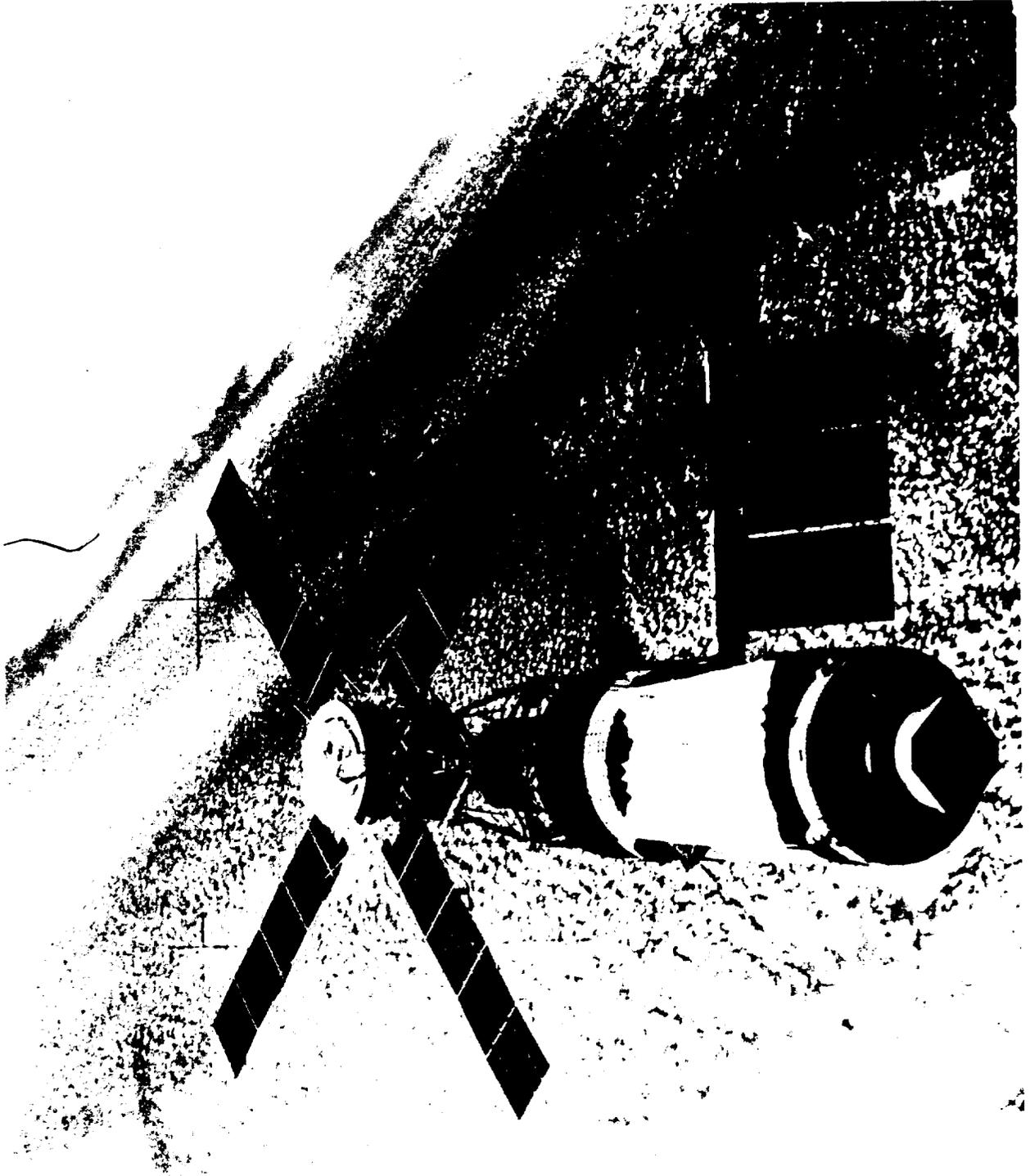


Figure I.A-2 Operational Skylab

B. Program Objectives

The Skylab program was conceived to conduct scientific investigations in a low earth orbit. Briefly the program can be divided into four broad categories summarized as follows:

1. Biomedical and Behavioral Performance. To determine and evaluate man's physiological responses and aptitudes in space under zero-gravity conditions and his postmission adaptation to the terrestrial environment, through a series of progressively longer missions, and determine the increments by which mission duration could be increased.

2. Man-Machine Relationships. To develop and evaluate efficient techniques using man for sensor operation, data selection and evaluation, manual control, maintenance and repair, assembly and set-up, and mobility involved in various operations.

3. Long Duration Systems Operations. To develop techniques for increasing systems life, for enduring long habitability periods and for maintaining extended mission control, plus investigate and develop techniques for inflight test and qualification of advanced subsystems.

4. Experiments. To conduct solar astronomy, earth resources, science, technology, and applications experiments that involve man when his contribution will improve the quality and/or yield of the results.

C. Skylab Evolution

The evolution of Skylab encompassed more than a decade of effort by NASA and Industry personnel. Many obstacles were overcome, which required the efforts of all participants to achieve all the original goals.

The first documented report to suggest the use of an S-IVB stage as a space laboratory occurred in November 1962 and served as a catalyst to formalize ideas that had yet to be published. By early 1965, center program analysts and development personnel were using such terms as "spent stage" and "wet" workshop in reference to the possibility of purging propellant from an S-IVB stage in space and converting the stage to a space laboratory. Interest and activities increased and by August 1965, National Aeronautics and Space Administration (NASA) Headquarters announced the establishment of an Apollo Application Program (AAP) office, which replaced the old Apollo Extension Systems Program. Effort accelerated on the concept of converting a spent S-IVB stage to a space laboratory and in December 1965 Marshall Space Flight Center (MSFC) received formal go-ahead to develop the Orbital Workshop (OWS). Additional consideration was given to the use of Gemini subsystems on the airlock splice experiment.

The first officially released schedule for AAP reflected a requirement for the launch of twenty-six Saturn IB and nineteen Saturn V launches. These launches involved three S-IVB/Spent Stage Experiment Support Modules (SSESM), three Saturn V Workshops, and four Apollo Telescope Mounts (ATMs) in addition to five lunar missions and two synchronous orbit missions. There were several schedule iterations during the "wet" workshop period that lasted through June 1969 and primarily reflected funding constraints through a reduced number of launches. Initially mission duration was set at a nominal 14 days with extended missions of up to 45 days.

Initially the AAP launch configuration consisted of a SSESM mounted on the forward end of a S-IVB stage and a Command and Service Module (CSM). Most experiments were biomedical and would be carried and performed in the Command Module (CM). Astronauts would enter the passivated S-IVB spent stage through the SSESM and activities primarily would amount to familiarization with zero-g locomotion in a controlled and enclosed environment. The crew would be quartered in the CSM.

Basic AAP concepts remained unchanged until December 1966 with the advent of a rendezvous and docking requirement in space using a Lunar Module (LM)/ATM configuration. Additionally, this new concept provided for the major step of making the S-IVB habitable by passivating and pressurizing the hydrogen tank in orbit. A two-gas atmosphere of oxygen and nitrogen replaced the S-IVB/SSESM one-gas oxygen system and incorporated a shirt-sleeve environment. At this time the require-

ments for the Airlock Module (AM) and Multiple Docking Adapter (MDA) were identified. Crew quarters were to be established in the S-IVB purged propellant tank with the storage of habitability equipment in the MDA.

Primary activities through the remainder of the "wet" workshop era reflected considerable change and addition of experiment requirements, the addition of solar array wings to the OWS for increased power capability, emphasis on the need for integration of payload requirements, elimination of lunar missions and conceptual studies involving the substitution of a "dry" for a "wet" workshop program. Additionally the announcement of specific basic objectives for AAP was made. The objectives were as follows:

- Long-duration space flights of men and systems, based on unique capabilities of man habitability, biomedical, and behavioral consideration and systems development.
- Scientific investigations in earth orbit based on solar astronomy, earth observation, and stellar astronomy.
- Applications in earth orbit based on meteorology, earth resources, and communications.

The MSFC was assigned the managerial responsibility for the AM and Lunar Explorer Module (LEM) to establish a satisfactory balance between Apollo and AAP and to place design integration under a single NASA center.

In July 1969 NASA headquarters announced the decision to convert from the "wet" to "dry" workshop configuration with significant changes identified as follows:

- Multiple Docking Adapter
 - Delete Orbital Workshop (OWS) experiment storage
 - Add Apollo Telescope Mount controls and displays
- Airlock Module
 - Add total mission atmospheric gas storage
 - Delete scientific airlock
 - Shroud configuration changed
 - Add Apollo Telescope Mount deployment mechanism
- Orbital Workshop
 - Substitute cold gas attitude control system for old hot gas system
 - Preinstall all equipment, expendables, and experiments
 - Add scientific airlock
- Lunar Module Ascent Stage
 - Deleted

The launch configuration for Skylab and the CSM are represented in Figure I.C-1.

With the "dry" workshop decision finalized, emphasis was directed toward establishing a technical baseline for system definition and design purposes. The release of the Cluster Requirements Specification (CRS) provided such a baseline and detailed design of the AAP systems proceeded on an expedited basis.

In February 1970 NASA Headquarters officially redesignated the AAP as the Skylab Program. Figure I.A-1 depicts the on-orbit Skylab cluster configuration as designed and essentially consisting of the ATM, MDA, OWS, AM and CSM.

Final design, manufacturing, qualification testing, and hardware acceptance were the primary Skylab events from January 1970 through September 1972. Selection of Skylab prime and backup crews also occurred during this period and names were released as follows:

	<u>Prime</u>	<u>Backup</u>
Skylab Mission 1:	Charles Conrad, Jr. Joseph Kerwin Paul Weitz	Russell Schweichart Story Musgrave Bruce McCandless
Skylab Mission 2:	Alan Bean Owen Garriott Jack Lousma	Vance Brand William Lenoir Don Lind
Skylab Mission 3:	Gerald Carr Edwin Gibson William Pogue	Same as Mission 2

With the arrival of the AM/MDA at Kennedy Space Center (KSC) in early October 1972, all modules came under KSC control and the final verification program was in full swing. The successful completion of the verification program culminated in the launch of the Skylab during May 1973.

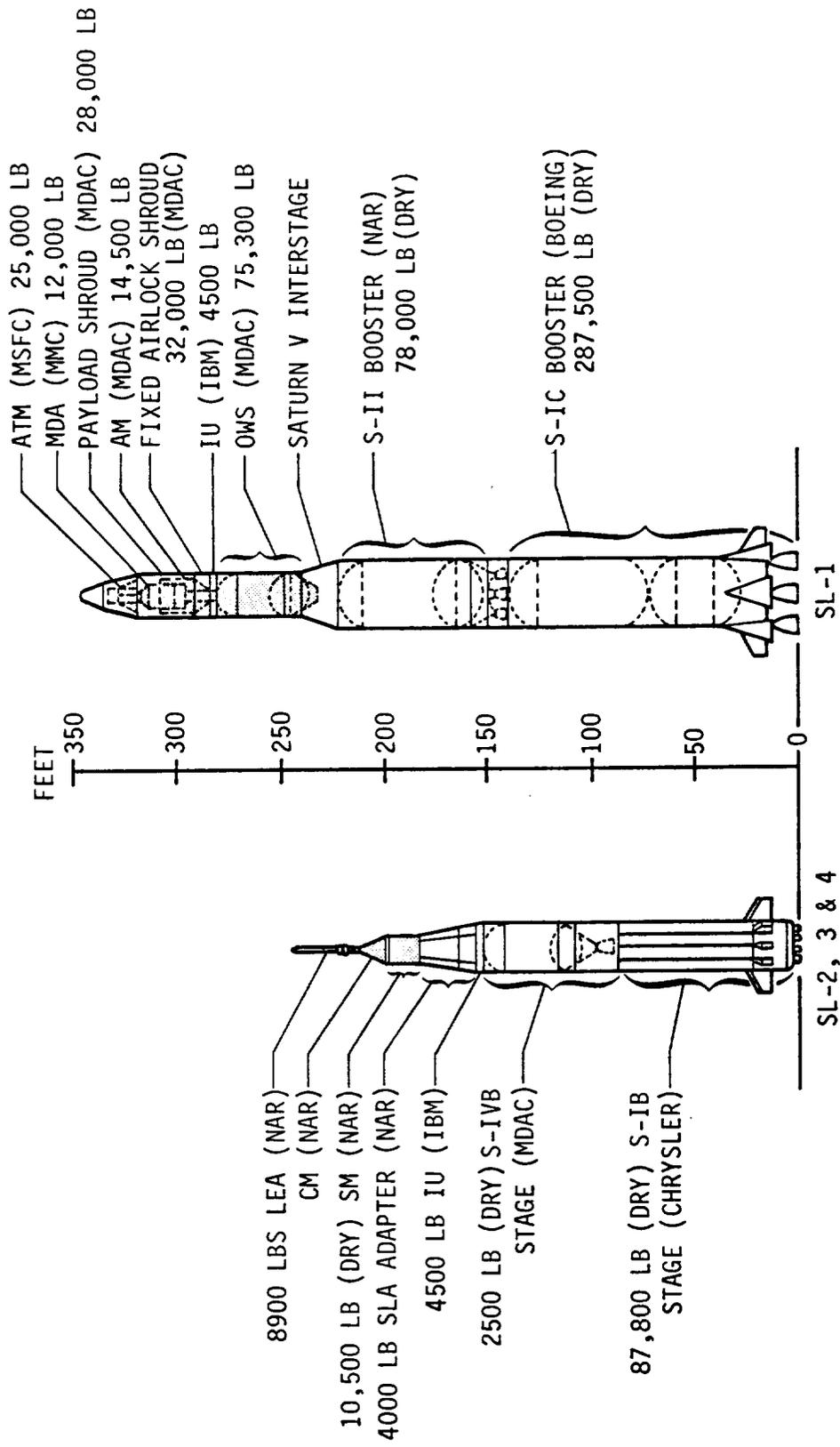


Figure I.C-1 Skylab Launch Configuration

D. Management Philosophy and Techniques

Although Skylab inherited much of its basic equipment and technology from Apollo and the programs that preceded it, the challenges it had to face were new and significantly more complex. Skylab embraced an unprecedented diversity of objectives, sophistication and variety of experiments. It was the first time that the development of an inhabited space vehicle had been physically and organizationally separated from the crew and mission-operations group.

To deal with these factors, a new division of responsibilities was instituted. MSFC was assigned hardware systems integration; JSC was assigned integration of mission and crew operations in addition to hardware responsibility for the Command and Service Module (CSM) and assigned experiments, and KSC was responsible for launch operations. Program offices established at the three centers came under overall management and direction of the Skylab Program Director in the Office of Manned Space Flight (OSMF).

MSFC had specific responsibility for developing elements of the flight hardware and related software, as follows:

- Saturn IB and Saturn V.
- OWS, Airlock Module (AM), and Multiple Docking Adapter (MDA).
- Apollo Telescope Mount (ATM).
- Payload Shroud (PS) for the Workshop.
- Assigned experiments.

Technical management was effected primarily through issue of coordinated requirements and performance specifications, operation of intercenter technical panels, and a series of formal reviews on a module and system basis.

A Skylab Program Specification called out the overall hardware performance requirements. It was issued and controlled by the Program Director. The specification control of systems, hardware, and test requirements was derived from program objectives. The translation of these objectives into specifications governing system definition, hardware design, and test and checkout criteria required a technical evaluation effort that involved conceptual and cost trade-offs, and, ultimately, implementation through contractual action with affected contractors. The Cluster Requirements Specification served as the controlling specification for system level requirements and was used as a baseline for development and/or finalization of Contract End Item (CEI) specifications for the modules, experiments, and associated ground support systems controlled by the center. Test and Checkout Requirements Specification Documents

(TCRSDs) were derived from the CRS and appropriate CEIs. The documents included module level TCRSDs as well as an integrated TCRSD for the testing program at KSC. The CRS also served as a controlling specification for the development of Interface Control Documents (ICDs) between interfacing contractors.

The control of program specifications and ICDs was effected through a comprehensive configuration management program tailored after the system used on the Saturn program. Documents were baselined contractually and the configuration management and change integration system provided rigid control and assessment techniques to assure compatibility between all affected program elements for any given change action.

The following intercenter technical panels formulated and documented intercenter interfaces and resolved related technical problems as necessary: Mechanical, Electrical, Instrumentation and Communications, Mission Requirements, Launch Operations, Test Planning, and Mission Evaluation. The panels were either jointly chaired by the hardware-development centers or a designated lead center.

Each Skylab experiment, module and major subsystem was subjected to the following formal reviews: The Preliminary Requirements Review (PRR), Preliminary Design Review (PDR), Critical Design Review (CDR), Design Certification Review (DCR), Configuration Inspection (CI), Certification of Flight Worthiness (COFW), Crew Systems Reviews and Flight Readiness Reviews (FRRs).

The PRR was the earliest formal review of the various concepts considered and of the concept selected to meet the mission objectives. It provided a means to insure coordinated understanding of the basic performance requirements throughout the entire program structure. During a PRR, each responsible organization element from the total Skylab organization had the opportunity to submit formal Review Item Discrepancies (RIDs) for resolution. Each RID was formally acted on by the PRR board. Design was then initiated.

The PDR was a technical review of the basic design approach conducted early in the detailed design phase. The CDR was a technical review of the specifications and drawings conducted when the detail design was substantially complete. In addition to the review of the end item design itself, its compatibility with other portions of the system was examined. Formal submittal and resolution of RIDs was also part of the PDR and CDR activities.

The DCR was conducted at the module level to provide assurance that hardware design was acceptable and compatible with program requirements.

The CI was an examination of the manufactured end-items against the specification requirements, released engineering drawings, and test results. It was conducted in two parts: before final system test, when the configuration and overall status of the equipment and its Ground

Support Equipment, as well as qualification test data, were examined; and shortly before delivery, when final systems test data and acceptance test data were examined.

The COFW certified that each flight stage and module constituted a complete and qualified item of hardware before shipment. The basis for certification was contained and maintained (traceable) in the acceptance data.

Crew Systems Reviews were conducted on a continuous basis throughout the program to assure compatibility between Skylab crews and operational systems on a man/machine basis.

The FRR was conducted at the module and cluster levels and stressed the operational readiness of the Skylab systems to perform as required during the mission.

Based on Apollo experience, effective use of special reviews was employed throughout the program. The Skylab Systems/Operations Compatibility Assessment Review (SOCAR) emphasized the total compatibility between design, development, test, and integration and operational aspects on a total systems basis and provided necessary insight to evaluate program needs and follow-on actions. Significant results were realized in assessment of hardware systems versus mission documentation and thus provided a high confidence in the operational readiness of the Skylab. Independent hardware reviews conducted late in the program through senior NASA individuals were vital in establishing confidence that design requirements were met and that hardware would function in a successful manner. These special reviews provided sufficient overall visibility to make final determination that launch schedules and mission objectives could be met.

Mission operations at JSC were conducted through the Flight Operations Management Room (FOMR) with MSFC involvement through a senior management representative. The official MSFC position as the result of problems or potential problems identified throughout the mission was formally presented in the FOMR and included MSFC representation as part of the decision making process. Mission support activities at MSFC were structured by system discipline through the Mission Support Groups (MSGs) and at the contractor level to assure that all action requests received a timely and well organized evaluation. Responses were finalized through the Huntsville Operations Support Center (HOSC) and transmitted to JSC as a formal MSFC position. Contractors were required to provide continuous support to the various MSGs locally and at the contractors facility to minimize response times as critical items developed.

The program director, or his deputy, chaired the Flight Management Team. Team members included Headquarters representatives and senior Center management and operations personnel. They provided program decisions based upon recommendations and options provided by the Flight Control/Support Team. MSFC participation on both teams was a vital part of the decision making process and contributed greatly to the overall success of Skylab.

E. Mission Definition

The definition of the Skylab program mission is identified below and includes mission objectives, Skylab Rescue (SL-R) mission, and the mission profile.

1. Mission Objectives.

a. SL-1/SL-2 Mission. The objectives for the SL-1/SL-2 mission, as assigned by the OMSF, follow.

- (1) Establish the Skylab Orbital Assembly in Earth Orbit
 - Operate the Orbital Assembly (SWS plus CSM) as a habitable space structure for up to 28 days after SL-2 launch.
 - Obtain data for evaluating the performance of the orbital assembly.
 - Obtain data for evaluating crew mobility and work capability in both intravehicular and extravehicular activity.
- (2) Obtain Medical Data on the Crew for Use in Extending the Duration of Manned Space Flights
 - Obtain medical data for determining the effects on the crew which result from a space flight of up to 28 days duration.
 - Obtain medical data for determining if a subsequent Skylab mission of up to 56 days duration is feasible and advisable.
- (3) Perform In-Flight Experiments
 - Obtain solar astronomy data for continuing and extending solar studies beyond the limits of earth-based observations.
 - Obtain earth resources data for continuing and extending multisensor observation of the earth from low earth orbit.
 - Perform the assigned scientific, engineering, technological and Department of Defense (DOD) experiments.

b. SL-3 Mission. The objectives for the SL-3 mission were as follows:

(1) Perform Unmanned Saturn Workshop Operations

- Obtain data for evaluating the performance of the unmanned Saturn Workshop (SWS)
- Obtain solar astronomy data by unmanned ATM observations

(2) Reactivate the Skylab Orbital Assembly in Earth Orbit

- Operate the orbital assembly (SWS plus CSM) as a habitable space structure for up to 56 days after the SL-3 launch
- Obtain data for evaluating the performance of the orbital assembly
- Obtain data for evaluating crew mobility and work capability in both intravehicular and extravehicular activity

(3) Obtain Medical Data on the Crew for Use in Extending the Duration of Manned Space Flights

- Obtain medical data for determining the effects on the crew which result from a space flight of up to 56 days of duration
- Obtain medical data for determining if a subsequent Skylab mission of greater than 56 days duration is feasible and advisable

(4) Perform In-Flight Experiments

- Obtain ATM solar astronomy data for continuing and extending solar studies beyond the limits of earth-based observations
- Obtain earth resources data for continuing and extending multisensor observation of the earth from the low earth orbit
- Perform the assigned scientific, engineering, technology and DOD experiments.

c. SL-4 Mission. The planned mission objectives for SL-4 were basically the same as those stated for SL-3. The opportunities mentioned previously, however, presented ample justification for extension of the mission and the attainment of more data.

2. SL-R Mission. The SL-R mission was unique to this program. No previous space program provided the capability to rescue spacemen. The SL-R mission was planned as a contingency mission to provide for the safe return to earth of the Skylab crew in the event that the docked CSM should fail and be unsafe for return. The next in-line CSM would be used as the SL-2 or SL-3 rescue vehicle; the backup CSM would be used for SL-4.

Installation of a field modification kit was required if a rescue situation occurred. The SL-R CSM would be launched with two crewmen, rendezvous and dock with the SWS, and return safely to earth with five crewmen. Without compromising the above goals, accomplishment of the following would have been considered:

- Return selected experiment payload data,
- Perform a diagnosis of the CSM failure,
- Configure the SWS for revisit.

3. Mission Profile. Planned profiles for the Skylab missions are briefly stated as follows:

a. SL-1/SL-2 Mission.

(1) Workshop Launch and Insertion into Orbit. The Workshop, incorporating the modified S-IVB, ATM, MDA, and AM was to be inserted into an orbit of approximately 235 x 235 n-mi. and 50° inclination and configured to await arrival of the manned CSM.

(2) CSM Launch and Insertion into Orbit. Nominal launch of the CSM was to be on the day following the Workshop launch. The CSM was to be inserted into an orbit of approximately 81 x 120 n-mi.

(3) CSM Rendezvous and Dock with the Workshop. The CSM was to enter a phasing orbit, rendezvous with the Workshop and dock to the MDA axial port. The CSM Service Propulsion System and Reaction Control System was to be used for rendezvous maneuvers.

(4) Workshop Operations. The crew was to activate the Workshop, configure the CSM systems for dependent operation and conduct experiments to demonstrate the SWS habitability. The mission was to be conducted for a period of up to 28 days with emphasis on medical experiments designed to test the effects of prolonged space flight. The ATM equipment was to be activated and its operation verified. Other experiments were to be conducted as assigned.

(5) Workshop in Storage Mode. Near the completion of the mission, the Workshop was to be placed in an operating mode suitable for storage.

(6) CSM Deorbit and Recovery. The CSM was to separate from the Workshop using the Service Module (SM) Reaction Control System. The SM Service Propulsion System was to perform the nominal deorbit burn with the SM Reaction Control System available as backup.

b. Revisit Missions (SL-3, SL-4).

(1) CSM Launch and Insertion into Orbit. The CSM was to be inserted into an orbit of approximately 81 x 120 n-mi.

(2) CSM Rendezvous and Dock with the Workshop. The CSM was to enter a phasing orbit, rendezvous with the Workshop and dock to the MDA axial port. The CSM Service Propulsion System and Reaction Control System was to be used for rendezvous maneuvers.

(3) Workshop Operations. The crew was to reactivate the Workshop, configure the CSM systems for dependent operation and obtain solar astronomy data using the ATM. Biomedical and other assigned experiments were to be performed.

(4) Workshop in Storage Mode. Near the completion of each mission, the Workshop was to be placed in an operating mode suitable for storage.

(5) CSM Deorbit and Recovery. The CSM was to separate from the Workshop using the Service Module (SM) Reaction Control System. The SM Service Propulsion System was to perform the nominal deorbit burn with the SM Reaction Control System available as backup.

F. Systems Design

Utilization of existing design technology and hardware was maximized on the Skylab program; however, new and complex requirements necessitated the application of new technology to various system elements. From the initial concepts of systems design through the verification and operational phases, the final success of Skylab was a direct result of effective systems integration techniques utilized by center management.

1. Preliminary Design. This period essentially encompassed the time frame between official program start in December 1965 through the decision to convert from the "wet" to "dry" workshop configuration in July 1969. Conceptual trade-offs were performed involving technical and cost considerations to define systems configurations for each Skylab iteration during this phase. Preliminary system design effort utilizing existing hardware from previous programs, primarily Apollo, progressed for many system elements. Detailed hardware design, however, developed at a slower pace since much of the total system had not been baselined.

2. Formal Design. Systems design entered a new phase with the decision to proceed with the "dry" workshop configuration in July 1969. Much of the effort performed during the preliminary design phase was still valid but extensive effort was required to establish a systems design compatible with "dry" workshop requirements. Following this decision, the development and baselining of the CRS resulted in a single document defining system level requirements and criteria for systems design. The formalization of the CRS as a single specification to control design responsibilities initiated the formal systems design phase. Individual Contract End Item specifications were aligned with CRS requirements and detail hardware and system element design efforts proceeded at the module and experiment levels under individual contractor and center controls.

As hardware design developed, the utilization of formal reviews was emphasized and brought into focus the need to assure the compatibility of the total Skylab system. Participation in these reviews was extended to manufacturing, quality, test and mission requirements personnel in addition to key center and contractor personnel involved in the hardware definition. Preliminary Design Reviews and Critical Design Reviews were performed and emphasized the compliance of the hardware against appropriate specifications. Compatibility of interface requirements with other hardware and system elements was stressed and required participation by other affected contractors. Ultimately the CDRs resulted in the release of baselined engineering and subsequent control through the configuration control system managed at the center level.

3. Design Verification. The initial design verification was accomplished through PDR and CDR activities during the formal design period and essentially assured hardware qualification and specification compliance. As the process of system build-up proceeded, the ultimate verification process was two-fold. Functional compatibility of the total system and its elements was demonstrated through a comprehensive testing program conducted at the end item, module, and experiment levels and ultimately through integrated testing of the total cluster at KSC. Emphasis was also placed on verification of the crew system interfaces with the system elements and was demonstrated through regularly scheduled crew system reviews conducted at contractor facilities and at key times during KSC activities. Extensive use of simulators provided further confidence that system design was compatible with crew capabilities. Secondly, the concept of formal program reviews was continued following the experience gained on Apollo with these reviews proving invaluable in establishing the necessary confidence that the total Skylab systems design was compatible with program objectives. Design Certification Reviews (DCRs), Spacecraft Acceptance Reviews (SARs), SOCARs, Hardware Integrity Reviews (HIRs), and Flight Readiness Reviews (FRRs) were the more significant activities conducted and respectively stressed design acceptability and formal acceptance of the hardware; total systems compatibility between hardware, software, and crew personnel; special review of critical hardware elements; and overall final readiness of the total system from a functional and operational aspect to meet launch and mission criteria. These reviews involved high level center and contractor management and technical personnel and were beneficial during the final evaluation process in determining system design acceptability and readiness for the Skylab missions.

G. Program Summary

Skylab was the first space laboratory and contained facilities and systems that were extremely sophisticated and represented the latest technological innovations. Basic systems were required to provide electrical power generation and distribution, environmental control, attitude control of the cluster, instrumentation, communications, caution and warning for crew safety, and crew habitability support. These systems were designed to support an eight-month mission with five of those manned. Laboratory facilities were provided to accommodate diverse experiments covering astronomy, earth resources, scientific investigations, biomedical evaluation, technology and special applications. This hardware was contained in five different major hardware elements (modules) which were manufactured by different contractors.

The integration of all requirements and hardware into a configuration that successfully fulfilled program objectives was a major MSFC responsibility. These Systems Engineering and Integration activities involved extensive participation of crew systems in the design review and testing of hardware, the integration of experiments into the respective modules, and the integration of the modules into an operational cluster. Additionally, close relationship with and involvement of flight operations personnel was required to assure compatibility of the Skylab systems and flight operations planning. The following summary identifies the effectiveness of the major hardware elements (module and experiments), crew systems, and Systems Engineering and Integration activities.

1. Airlock Module. The AM was designed and fabricated by the Eastern Division of McDonnell Douglas Astronautics Company (MDAC-ED), who also fabricated the ATM Deployment Assembly (DA) and Fixed Airlock Shroud (FAS). See Figure I.G-1 for basic AM configuration. The original concept of the AM was to provide an interconnecting tunnel and airlock between the CSM and the OWS. As the program matured, expanded requirements were imposed and ultimately basic features were provided as follows:

- Interconnecting passage between the MDA and OWS
- Airlock, hatch and support system for extravehicular activity
- Purification of the Skylab atmosphere
- Environmental control of the Skylab atmosphere (cooling only for the MDA and OWS)
- Atmospheric supply and control
- ATM launch support and orbital deployment provisions
- Electrical Power control and distribution

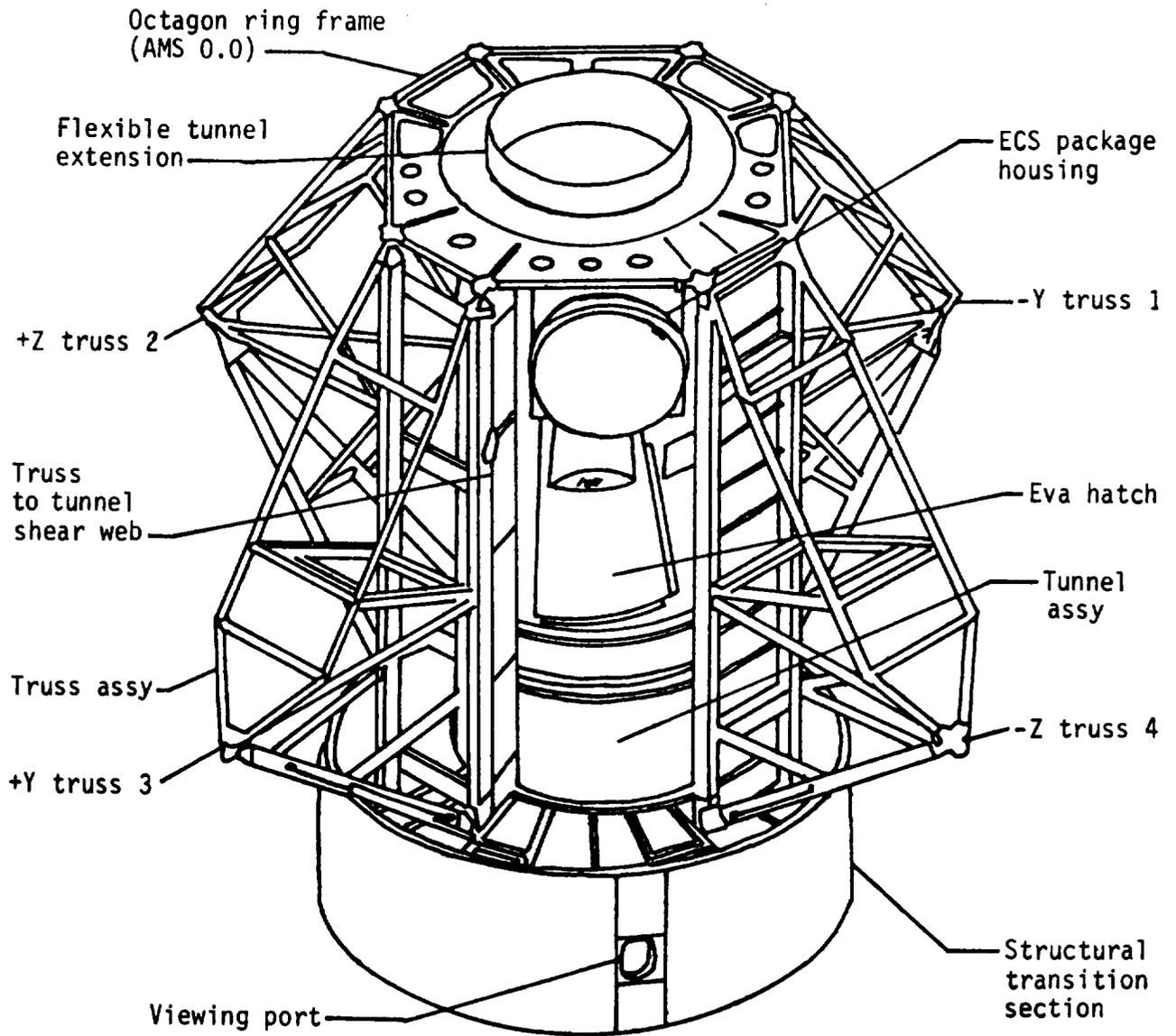


Figure I.G-1 Airlock Module

- Real- and Delayed-time data
- Cluster caution and warning
- Command system link with ground network
- Very High Frequency (VHF) ranging link for CSM rendezvous
- Controls and displays
- Teleprinter
- Experiment installation of D024 sample panels
- Experiment antennas for Earth Resources Experiment Package (EREP), and radio noise burst monitor
- Structural support of the ATM, AM, MDA, and FAS

In support of these basic features, system design capabilities were provided as follows:

a. Structures and Mechanical

(1) The AM configuration included four basic structural sections. The sections were the Structural Transition Section (STS), which included the radiators, the tunnel assembly, the flexible tunnel extension assembly, and the support truss assemblies.

(a) The STS provided the structural transition from the MDA to the Airlock Tunnel. The STS structure was a pressurized aluminum, welded cylinder 47 inches long and 120 inches in diameter of stressed skin and semimonocoque construction. The STS bulkhead provided the transition from 120 to 65 inches diameter to mate with the tunnel assembly. Machined rings were used to make a typical flanged, bolted interface. Four double-pane glass STS viewing ports allowed visibility. Each window was protected when not in use by an external, removeable cover assembly, actuated from inside the STS by a manual crank. The cover served a dual purpose: to minimize meteoroid impacts on the glass, and to minimize heat loss from the cabin area.

The Airlock Module Radiator panels served as a meteoroid shield for part of the pressure vessel skin in addition to their basic function as space radiators. Radiators were mounted on both the STS and MDA. To minimize development and thermal testing, the panels were designed of the same materials and detail construction used on the Gemini radiator.

(b) The tunnel assembly was a pressurized semimonocoque aluminum cylinder 65 inches in diameter and 153 inches long. Two internal circular bulkheads with mating hatches divided the tunnel assembly into three compartments. Hatch seals and latching mechanisms were provided in the bulkheads.

- The forward compartment was 31 inches long and interfaced with the STS section. It provided support for stowage containers, tape recorders, and miscellaneous equipment.
- The center (lock) compartment was 80 inches long and included a modified Gemini crew hatch for ingress/egress during Extravehicular Activity (EVA).
- There were two internal hatches, located forward and aft. One hatch was used for EVA.

(c) The flexible tunnel extension assembly was a flexible convolute metallic bellows 42.5 inches inside diameter by 13 inches long and formed a pressurized passageway between the AM and OWS.

(d) There were four truss assemblies of similar basic design. Minor modifications were required on each truss assembly to support miscellaneous equipment. The trusses were fusion welded aluminum tubes. Nitrogen tanks were mounted on gimbals to isolate them from truss deflections and resulting loads.

(2) The DA consisted of two aluminum tube truss assemblies connected by a pair of trunnion joints, which allowed the upper truss assembly to rotate 90° to deploy the ATM. The DA also supported wire bundles, experiments, antennas, and miscellaneous equipment. The lower truss assembly was made up of bipods, with the base of the bipods attached to the top ring of the FAS. A framework atop the upper truss assembly provided mounts for the four ATM attachment points (rigidizing mechanisms). These rigidizing mechanisms attached to the ATM through four adapter fittings. During ground operations and launch, the ATM was supported by the PS but loosely attached to the DA by the rigidizing mechanism in a floating position. Following PS separation, the springs in each rigidizing mechanism retracted and rigidly attached the ATM to the DA. On the ground, alignment of the ATM was provided by the DA attachments at the rigidizing mechanisms. The DA rotation system provided a means of rotating the ATM from its launch position to its in-orbit configuration. The rotating system consisted of the following major components.

- Two release mechanisms each redundantly released the upper truss to allow rotation.
- Two trunnions provided the pivots to rotate the upper truss.
- Two deployment reels provided the redundant means to pull (rotate) the ATM into the deployed position.
- The latch mechanism was used to retain the ATM/DA in the deployed position.

(3) The FAS was a ring-stiffened, thick-skinned cylinder approximately 80 inches in height and 260 inches in diameter. Inter-costals distributed concentrated loads introduced by the DA, AM and

oxygen (O₂) tank support points. Two doors were provided in the FAS; one for access to the FAS interior and the AM EVA hatch during ground operations and the other for access to ground umbilical connectors. Four antennas; two deployable discons, and two Ultra High Frequency (UHF) antennas were mounted on the FAS. The FAS structure also contained egress handrails, work platform, film cassette tree supports, film transfer boom (also called TEE), a TEE hook stowage box and lights.

b. Environmental/Thermal Control Systems (ECS/TCS). The AM ECS/TCS consisted of the following subsystems:

(1) A gas system permitted prelaunch purge, stored high-pressure O₂ and Nitrogen (N₂) and regulated pressure and distribution for cabin atmosphere and other uses.

(2) The atmospheric control system provided moisture removal, carbon dioxide and odor removal, ventilation, and cabin gas cooling. Moisture was removed from the cluster atmosphere by condensing heat exchangers and molecular sieves. Carbon dioxide and odor were also removed by the molecular sieve system. Ventilation was provided by fans and condensing heat exchanger compressors. Gas cooling was provided by the condensing and cabin heat exchangers.

(3) The condensate system provided the capability of removing atmospheric condensate from the condensing heat exchangers, storing it, and disposing of it. In addition the condensate system provided the capability of removing gas from the liquid gas separator and disposing of it as well as providing a vacuum source for servicings/deservicings.

(4) The suit cooling system provided astronaut cooling during EVA and Intervehicular Activity (IVA) by circulating temperature-controlled water through the umbilical, Liquid Cooled Garment (LCG), and Pressure Control Unit (PCU) of the astronaut's suit.

(5) The active cooling system consisted of two separate, redundant loops for active cooling of the suit cooling module, atmospheric control modules, selected experiment modules and coldplate-mounted electrical/electronic equipment.

(6) The ATM Control and Display (C&D) panel and EREP cooling system provided cooling to the ATM C&D panel and to EREP components by circulating water to the equipment.

(7) The passive thermal system used thermal coating, thermal curtains, and insulation material to control the gain and loss of heat both internally and externally.

c. The Electrical Power System (EPS). The EPS housed by the AM contained eight nickel-cadmium batteries and their charger/regulators to power the many electrical devices aboard the Skylab. These batteries

provided up to 3,830 watts of power every orbit and were recharged by the OWS Solar Array.

Power Conditioning Group (PCG) outputs were applied to the various AM EPS buses by appropriate control switching provided on the STS instrument panel or by ground control via the AM Digital Command System. Each PCG provided conditioned power to using equipment and recharged the batteries during the daylight period. A switching arrangement permitted the powering of all eight PCGs from one solar array throughout the Skylab missions.

d. Sequential System. The Sequential System of the Airlock controlled mission events to establish the initial orbital configuration of Skylab. Using commands from the launch vehicle Instrumentation Unit (IU), backed by a command capability from the ground, the following events were planned to follow launch:

- PS jettison
- Discone antenna deployment
- DA activation to position the ATM
- OWS and ATM solar wing deployment
- Venting operations
- OWS radiator shield jettison
- Attitude control transfer

Although the Airlock sequential system functioned as required, an OWS meteoroid shield malfunction prevented automatic deployment of the OWS solar wings.

e. Instrumentation System. The Airlock Instrumentation System sensed, conditioned, multiplexed, and encoded vehicle, experiment, and biomedical data for transmission to ground stations in either real time or recorded delayed time. In addition, it provided data for onboard displays, and through hardline, enabled readout during ground checkout. The system included the following subsystems:

- Oxygen Partial Pressure Sensing System
- Dew Point Sensor
- Quartz Crystal Microbalance Contamination Monitor
- Acoustic Noise Measuring System
- Signal Conditioning Packages

- Carbon Dioxide Transducers
- Flowmeters
- Temperature Sensors

f. Communications System. The Communications System transmitted and received voice, instrumentation data, and television data between crewmembers in the Skylab and on EVA; crewmembers and ground tracking stations; Skylab systems and ground tracking stations, and between Skylab and the rendezvousing CSM. The Communications System consisted of the following subsystems:

(1) Audio-System. Used in conjunction with the Apollo Voice Communications System to provide communications among the three crewmen and between Skylab and the Spaceflight Tracking and Data Network (STDN).

(2) Digital Command System (DCS). A sophisticated, automatic command system that provided the STDN with real-time command capabilities for the AM, OWS, and MDA. The DCS permitted control of experiments, antennas, and cluster system functions.

(3) Teleprinter. In conjunction with the AM receiver/decoders, the teleprinter provided paper copies of data transmitted by the STDN.

(4) Time Reference System (TRS). Provided time correlation to the PCM Data System, automatic reset of certain DCS commands, automatic control of the redundant DCS receiver/decoders, and timing data to the EREP and onboard displays in the AM and OWS.

(5) Telemetry Transmission System. Used in conjunction with the Airlock Antenna System, the Telemetry System provided Radio Frequency (RF) transmission capability to the STDN during prelaunch, launch, and orbit for real-time data, delayed-time data, delayed-time voice, and emergency voice (during rescue transmission), in both stabilized and unstabilized vehicle attitudes. The system included four telemetry transmitters, three of which could be operated simultaneously during orbital phases.

(6) Antenna System. Consisted of a modified Gemini Quadriplexer, two modified Gemini UHF Stub Antennas, four RF Coaxial Switches, two Antenna Booms, two Discone Antennas, and a helical VHF Ranging Antenna.

(7) Rendezvous Systems. Consisted of a VHF Ranging System and four tracking lights. The systems facilitated rendezvous of CSMs with the SWS. The Airlock Equipment comprised a VHF Transceiver Assembly, a Ranging Tone Transfer Assembly and a VHF Ranging Antenna.

g. Caution and Warning (C&W) System. The system monitored critical Skylab parameters and provided the crew with audio/visual alerts to imminent hazards and out-of-specification conditions that could lead to hazards. Emergency situations resulted in a Klaxon horn sounding throughout the Skylab vehicle. C&W conditions were brought to the crew's attention through crew earphones and speaker/intercom panels. Emergency parameters involved:

- MDA/STS fire
- AM aft compartment fire
- OWS forward/experiment/crew compartment fire
- Rapid change in vehicle pressure

Warning parameters included:

- Low O₂ partial pressure
- Primary and Secondary coolant flow failure
- AM and ATM regulated power bus out-of-specification
- Cluster attitude control failure
- EVA suit cooling out-of-specification
- AM and CSM crew alerts

Caution parameters consisted of:

- Mole sieve overtemperature, high carbon dioxide content, flow failure, and sequencing
- OWS ventilation out-of-specification
- Rapid condensate tank pressure change
- Primary and Secondary coolant temperature out-of-specification
- C&W system bus voltage out-of-specification
- EPS voltages out-of-specification
- ATM attitude control system malfunctions
- ATM coolant system malfunctions

h. Crew Systems. The Airlock functioned as a nerve center for monitoring and operating many complex vehicle systems automatically or by the crew.

(1) STS-Primary crew controls for AM systems:

- EPS
- EPS; Molecular Sieve
Atmosphere Fans
Coolant Control
Condensate System
- IVA Control Panel
- Flight Logbook and Records
- Cluster C&W Monitor System
- O₂/N₂ Gas Distribution System

(2) Lock Compartment - EVA/IVA Operations

- EVA/IVA Control Panels
- Internal and EVA Lighting Controls
- Compartment Pressure Displays
- Vacuum Source

(3) Aft Compartment

- OWS Entry Lighting
- Thermal Fan and Valve Control
- M509 Recharge Station

(4) Other AM Crew Systems included the following:

- Mobility Aids
- Communications; Placement of internal voice
communications
- Stowage

i. Experiments. The experiments and experiment support equipment which were mounted on the Airlock are as follows:

(1) D024 Thermal Control Coatings. Evaluated selected thermal control coatings exposed to near-earth space environment.

(2) S193 Microwave Radiometer Scatterometer/Altimeter. Determined land/sea characteristics from active/passive microwave measurements.

(3) S230 Magnetospheric Particle Collection. Measured fluxes and composition of precipitating magnetospheric ions and trapped particles.

(4) Radio Noise Burst Monitor. Permitted prompt detection of solar flare activity.

(5) M509 Gaseous Nitrogen (GN₂) Bottle Recharge Station. Supporting hardware for recharging three OWS-stowed GN₂ bottles.

The successful Airlock System performance during the Skylab Program indicates the effectiveness of the design, fabrication, and test activities that preceded the flight mission. It also indicates the effectiveness to the mission support activity in responding to discrepant conditions and providing real-time workaround plans.

The major conclusion that can be drawn from a program point of view is that the Airlock program philosophy of maximum use of existing, qualified space hardware with extensive use of system engineering analysis and previous test results to identify the minimum supplemental test program that was required to complete system verification was proved as a valid, economical approach to a successful mission.

All Airlock systems were fully operational at the end of the mission. The system discrepancies that remained were relatively insignificant and had no effect on the capability to adequately support all mission objectives.

2. Multiple Docking Adapter. The MDA structure was fabricated by MSFC and outfitted by Martin Marietta Aerospace. It was originally conceived to extend the capability of the OWS to allow selected spacecraft to rendezvous and dock with the laboratory. After that initial concept, the functional capability of the MDA was expanded to satisfy additional requirements as the program evolved. Refer to Figure I.G-2 for the general MDA configuration. The MDA provided three basic capabilities; a docking facility, an environmentally controlled work and storage area, and an interface between the SWS elements and the CSM. Specific features in these categories were as follows:

- Docking Facility. An axial docking port was provided for normal CSM docking and a radial docking port was provided for emergency rescue or backup docking use.

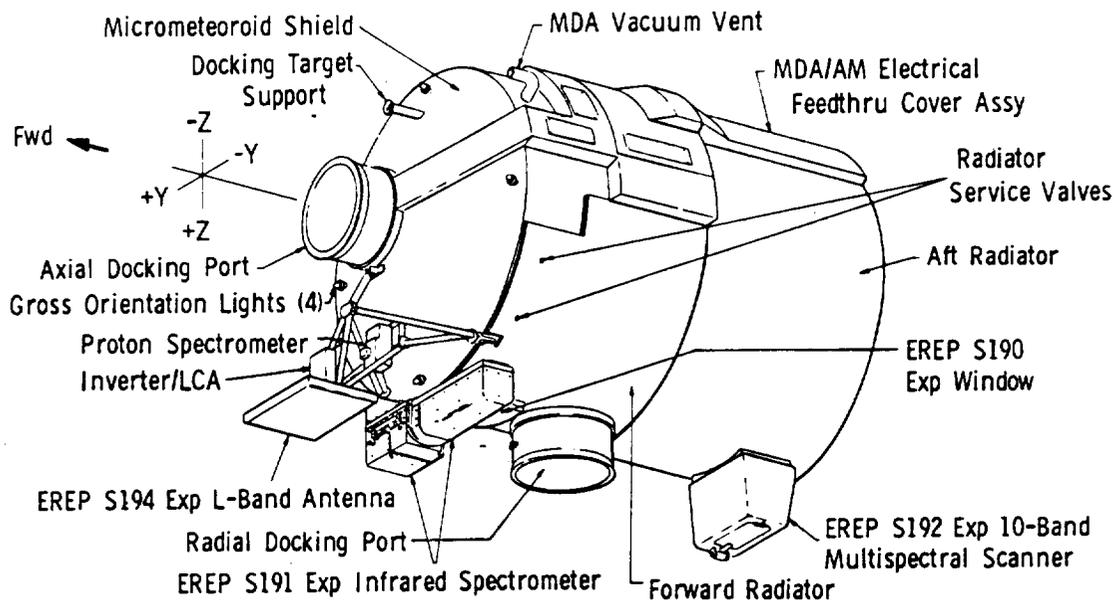


Figure I.G-2 Multiple Docking Adapter

- Environmentally Controlled Work and Stowage Area. The environmentally controlled work and stowage area capabilities and features were:

A pressurized passageway between the docked CSM and the AM/OWS

Work stations to support crew operations

Mounting and operation facility for experiments

Mounting and operation facility for the ATM C&D Console

Control and monitoring for the Radio Noise Burst Monitor (RNBM) and Proton Spectrometer

Crew intercommunication and C&W facility

Mounting and operation of the 16 mm Data Acquisition Camera (DAC)

Passive Thermal Control (External insulation)

Active Environmental Control (atmospheric ventilation, orbital venting, and external radiators)

Optical windows

Meteoroid protection

MDA lighting

Structural mounting (external) for the L-Band Antenna

Signal conditioning and instrumentation sensors

Stowage for cluster hardware and commodities

- Interface between SWS Elements and the CSM. The MDA provided a physical interface between the SWS and the CSM to accomplish the following:

Access between the CSM and the AM/OWS

Distribute electrical power to the CSM

Transfer of control, instrumentation, television (TV), and communication signals between the MDA/AM/OWS and the CSM.

To satisfy the basic functions imposed on the MDA, system design capabilities were provided as follows:

a. Structures. The MDA was a 10 foot diameter, 17.3 foot long pressure vessel that weighed approximately 14,000 pounds fully equipped. The MDA had two docking ports, one primary and one backup, designed for docking the CSM. External and internal mountings were provided for earth viewing experiment sensors. Film stowage vaults, equipment stowage containers, tape recorders, and TV equipment were installed internally. Controls and displays for EREP and ATM experiments were installed in the MDA. Work stations and mountings for scientific experiments performed inside the MDA were also provided. The MDA exterior structure consisted of radiator panels, meteoroid shields, insulation blankets, an electrical wiring tunnel, an L-Band truss for supporting the Inverter/Lighting Control Assembly (I/LCA), Proton Spectrometer, S194 L-Band Antenna and the S194 Electronics, structural support for EREP experiments S191 and S192, orientation lights, and docking targets.

The structure also contained four windows to provide viewing capabilities for Earth Resources Experiments. The windows were designed to meet optical requirements of the experiments and to provide MDA pressure integrity.

b. Thermal Control. Thermal control of the MDA was provided by a combination of passive and active subsystems. The passive subsystems limited the heat loss from the MDA interior to a value that would allow the active subsystem to control the internal temperature. The passive subsystem consisted of insulation blankets, fiberglass standoffs, paints, coatings, and low-emissivity aluminized Mylar tape. The active thermal control subsystem consisted of wall heaters, and thermostats, docking port heaters and thermostats, and a self-contained subsystem that controlled S190 window and frame temperatures. Temperatures within the MDA were also controlled by the air circulation subsystem and coolant loops.

c. Environmental Controls. The mechanical environmental control system included five major subsystems: ventilation, MDA/CSM hatch pressure equalization, MDA vent, M512 experiment vent, and ATM C&D panel/EREP cooling.

The ventilation subsystem consisted of fans and ducts. Three STS/MDA ducts provided cooled atmosphere from the STS into the MDA. A mol sieve duct introduced purified (carbon dioxide removed) atmosphere from the AM to the MDA. Fans for these ducts were located in the AM and atmosphere circulation in the MDA was provided by two fan/shroud/diffuser assemblies that controlled the air velocity at the crew stations. One additional fan/shroud/diffuser assembly was coupled to a flexible duct to circulate ambient MDA atmosphere to the CSM.

The MDA/CSM hatch pressure equalization subsystem provided a means of equalizing the atmospheric pressure between the CSM and the MDA after CSM docking and before SWS entry. Each docking port hatch was equipped

with a visual differential pressure gage and a manually-operated valve. Equalization of pressure across the hatch was achieved by opening the valve.

During launch, the MDA internal atmosphere was vented through the MDA vent subsystem. The venting was accomplished by two motor operated vent valves connected in series for closure redundancy. The internal valve opening was capped by the astronauts after entry into the MDA using a special sealing device.

The vent subsystem for experiment M512, Materials Processing in Space, provided a means of venting the experiment chamber to space. Venting was accomplished through two manually operated valves connected in series for redundancy. Experiment M512 battery venting to space was provided by an additional valve on the venting control panel.

The ATM C&D Panel/EREP coolant subsystem provided a flow of inhibited water coolant to electronic cold plates in the ATM C&D/EREP system. A manually operated four-port selector valve provided the means of directing the coolant to only the ATM C&D Panel or to both this panel and the EREP system. The coolant carried the heat generated by the electronic equipment to the AM where the heat was transferred through the AM heat exchanger to the AM coolant system.

d. Electrical. The MDA Electrical System operated within the overall cluster power systems and distributed electrical power for the functional operation of MDA systems and docked CSM systems. The MDA received all its electrical energy across the AM interface from the OWS/AM and ATM power systems.

Specific features of the electrical system included electrical interconnections and circuit breaker control between MDA electrical components and between the MDA and other module interfaces. Power was provided for interior lights, external running lights, heaters, utility outlets, fans, and MDA experiments.

e. Instrumentation and Communication (I&C). The I&C system of the MDA operated as part of the overall ATM, AM, and CSM systems to perform telemetry, TV, audio and C&W functions in the MDA. More specifically, these functions consisted of astronaut-to-astronaut voice communications, biomedical monitoring, fire detection sensing and warning, MDA statusing and environmental monitoring, portable TV camera coverage, and ATM TV camera operation.

The functions were accomplished by four subsystems within the I&C system. The communications subsystem consisted of three speaker intercom assemblies, which provided an audio interface and an information transfer link to the AM data acquisition subsystem, communicated temperature (both internal and external), pressure, and video selector switch position data through the MDA to the AM for transmission.

The TV subsystem consisted of a TV input station, a video selector switch, and a video tape recorder. The system provided an input interface for the portable TV camera, conditioned video signals from the TV camera or ATM camera, and provided for real-time TV transmission or recording of video and audio data for subsequent replay.

The C&W subsystem performed fire sensing detection and provided visual and audible signals that warned of potentially hazardous conditions in the orbital assembly. These signals were provided through the speaker intercom assemblies.

f. Experiments. The MDA provided support and operating facilities for the EREP experiments, corollary experiments, manufacturing-in-space experiments, and the ATM C&D Console. The EREP consisted of the S190A Multispectral Scanner, S193 Microwave Radiometer/Scatterometer/Altimeter, S194 L-Band Radiometer, EREP C&D Panel, and two Tape Recorders. Corollary experiments included the S009 Nuclear Emulsion Experiment, RNBM, and the Proton Spectrometer.

g. Crew Systems. The MDA Crew Systems provided for the protection, comfort, and assistance of the crewman and consisted of crew operational equipment and stowage containers. The crew operational equipment included flight data file, tools, a fire extinguisher, an O₂ pack and mask, speaker intercoms and communication headsets, portable equipment, utility cables, cameras and accessories, maneuverability equipment, and miscellaneous aids. The stowage containers and stowage provisions provided launch and orbital stowage of crew and experiment equipment.

The MDA flight data file included onboard data, launched on SL-1, which was necessary to support inflight crew operations through SL-2, SL-3, and SL-4 missions. The file consisted of checklists, logs, note tablets, maps, star charts, update pads, schematics, and malfunction procedures.

Tools for operational and contingency use were located at strategic points, such as contingency hatch opening tools which were mounted on the axial hatch. Other tool kits and loose miscellaneous hand tools were available in the MDA contingency tool containers.

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Mission performance of the MDA was considered excellent. The following summary presents specific performance comments against the three basic capabilities provided by the MDA.

- Docking Facility. The MDA axial docking port facility was used by each CSM crew in accessing the orbiting laboratory. There were no anomalies reported in the operations of this port facility. The first crew experienced some difficulty in obtaining a hard dock with the MDA but this was resolved in real-time and corrected through CSM probe and docking procedure modifications.

The MDA radial docking port was not used during the mission.

- Environmentally Controlled Work and Stowage Area. The performance of the MDA in providing accessible work stations, crew protection and comfort, and adequate stowage for designated hardware was within specified limits. The environment was, with the exception of a brief period early in the mission, within the comfort zone of the crew. An exception occurred during the employment of contingency thermal management techniques that were imposed to alleviate the excessive temperatures in the OWS. The high temperatures experienced were the direct result of OWS Meteoroid Shield and Solar Array failures, which occurred during launch. The remainder of the MDA, as a work and stowage area, had been verified before launch. This effort proved to be satisfactory because no significant comments were received from the three crews that would suggest poor access, limited work envelopes, limited stowage, inadequate electrical interfaces, or potentially dangerous conditions existed in the MDA.
- Interface between the SWS Element and the CSM. The MDA interfaces with the SWS and the axially docked CSM were nominal throughout the Skylab mission with no problems reported.

3. Orbital Workshop. The OWS was designed and fabricated by the Western Division of the McDonnell Douglas Astronautics Company (MDAC-WD) and was a converted S-IVB/IB stage from the Apollo program. The general configuration of the OWS is shown in Figure I.G-3. The function of the OWS was to provide primary living and working accommodations for the crew, experiment laboratory accommodations, stowage for supplies, and approximately one-half of the Skylab electrical power. Specifically, the OWS contained the following features:

- Internal;
 - Crew habitation area for sleeping, food, water, and waste management,
 - Areas for recreation and experimentation,
 - Facilities for stowage of supplies.
- External;
 - A Meteoroid Shield system designed to increase the probability of no pressure loss equal to or greater than 0.995 from the habitation area.
 - A Solar Array System designed to provide electrical power to the AM power distribution and control system.
 - A Thruster Attitude Control System designed to provide primary attitude control through the ATM control moment gyroscopes (CMG) spinup and backup/supplemental attitude control and CMG desaturation, for maneuvers, and docking transients.

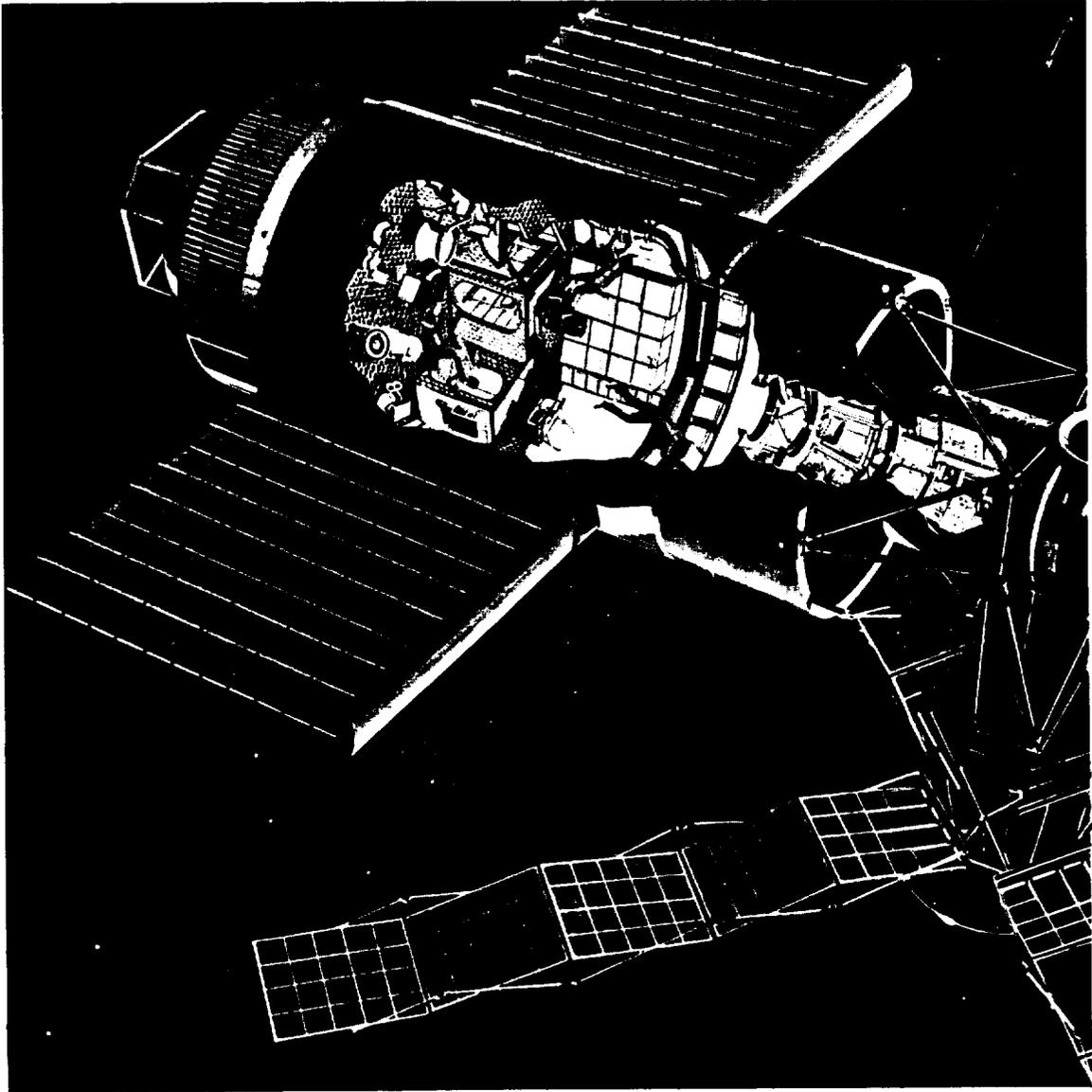


Figure I.G-3 Orbital Workshop

System design capabilities were provided to support OWS functions as follows:

a. Structural System. The OWS structural system was a modified S-IVB/IB stage. It consisted of a forward skirt, propellant tanks, an aft skirt, a thrust structure, and a main tunnel. The skirts and main tunnel served the same function for the OWS as they did for the S-IVB, i.e., to carry structural loads and accommodate externally mounted equipment and plumbing/wiring. The thrust structure had no J2 engine thrust loads to transmit, but otherwise it was used similarly to its S-IVB use. It carried loads and accommodated installation of additional equipment and integration hardware external to the OWS.

Modification of the S-IVB propellant tanks for the OWS was much more involved. A larger, reusable entry hatch replaced the S-IVB hatch in the forward dome of the Liquid Hydrogen (LH₂) tank. A side panel was added to the LH₂ tank for ground access only and provided entry into the tank for modifications, installations, and checkout. Three other apertures were included to provide an orbital viewing window and to accommodate two scientific airlocks (SALs) which provided the capability to deploy experiments external to Skylab.

Internally, the LH₂ tank modification consisted first of fully "papering" the polyurethane tank wall insulation with aluminum foil to fireproof the habitation area. A pair of grid floors that enclosed the crew quarters were installed and crew quarters that consisted of a wardroom, waste management and sleep compartments, and a medical experiment compartment were included.

The S-IVB Liquid Oxygen (LOX) tank was converted to a waste tank for the disposition of Skylab trash. The tank was compartmented with screens; one compartment used to collect liquid waste that was vented overboard through a nonpropulsive vent. The common bulkhead between the habitation area and the waste tank was reworked at the center for the installation of a trash lock through which trash was passed by the Skylab crews.

b. Meteoroid Shield System. A shield for the OWS habitation area protection against meteoroid penetration was afforded. The probability against pressure loss from penetration was equal to or greater than 0.995. The shield, made from aluminum sheet, was pretensioned against the tank wall for launch and ascent. It was to be released on orbit by ordnance severance of tie-down straps and was to deploy to a standoff distance from the tank wall of five inches. The deployment was to have been accomplished by energy stored in torsion bar springs installed at the forward and aft skirts. The shield, which after deployment would envelope the habitation area, had thermal coatings to provide passive thermal control for the Workshop.

c. Environmental/Thermal Control Subsystem. The ECS/TCS design was based on passive thermal control of the OWS environment with

augmentation by convective heating and cooling of the atmosphere during manned phases and radiative heating of the internal structure during unmanned phases. The ECT/TCS was thus made up of two basic subsystems: an active TCS including ventilation and a passive TCS.

The passive TCS consisted of optical property control of the OWS interior and exterior surfaces, High Performance Insulation (HPI) on the forward dome, polyurethane insulation lining on the inside of the OWS pressure shell, and heat pipes attached to structural penetrations of the interior insulation. The exterior surface finishes and the HPI blanket controlled the net energy balance between the OWS and the external space environment. The heat transfer rates from the habitation area to the meteoroid shield, and from the forward and aft dome areas, were regulated by surface finish control. Also, the interior habitation area wall temperatures were made more uniform with optical property control of these surfaces and with heat pipes.

The active TCS provided continuous control of the OWS internal environment during periods of astronaut habitation. The cabin gas temperature was controlled by cabin gas heat exchangers in the AM and by three convective heaters. Reconstituted air from the AM was mixed with recirculated air in the OWS. Before habitation, radiant heaters maintained temperatures above the minimum levels to satisfy food and film storage requirements.

d. Thruster Attitude Control System (TACS). For most of the eight-month long Skylab mission, the primary source of attitude control was the three CMGs located on the ATM. The CMGs provided the pointing accuracy and stability necessary for many Skylab astronomical and Earth Resources experiments, and maintained the solar inertial attitude necessary for the Skylab solar arrays. A propulsive attitude control system (ACS) was needed to provide control during CMG spinup (the first ten hours of the mission), to handle docking transients and large maneuvers beyond the capability of the CMGs, to desaturate the CMGs when necessary, and to provide a contingency capability in case of CMG failure. The system-designated TACS provided over 81,000 pound/second of impulse. A high thrust level of 50 pounds was required at the start of the mission for separation transients, a 20 pound thrust minimum was required for each of the three dockings with Apollo CMs, and a 10 pound minimum was specified for the rest of the mission. The system was a blow-down system using GN₂ as the propellant. Two modules of three thrusters each, 180° apart on the OWS aft skirt used quad-redundant valves for each thruster.

e. Solar Array System (SAS). The SAS for OWS was made up of two wings, each consisting of a beam fairing and three wing sections. Each section contained ten identical active solar panels for a total of 30 panels per wing or 60 for the complete system. The system supplied electrical power to the AM for distribution to equipment requiring power. The SAS provided an average of 10,496 watts between 51 and 125 volts during the sunlit portion of each orbit.

For launch and ascent of SL-1 the SAS beam fairings that housed the array were stowed snugly against the OWS meteoroid shield/tank structure. A GN₂ ground purge was introduced into the beam fairings to insure an atmosphere environment around the stowed array of 50 percent relative humidity or less. During launch the beam fairings were vented to preclude over-pressurization of the structural fairings.

After insertion of SL-1 in orbit, planned operation was to have been that an ordnance severance system would release the SAS beam fairings for deployment. The deployment was to have been accomplished with a viscously damped spring actuator. Subsequently, the wing sections were to have been released and deployed from the beam fairing by similar systems. The beam fairings and wing section were to have been mechanically latched in the deployed positions.

f. Electrical Power Distribution System (EPDS). The EPDS provided the means for power distribution from the AM to all OWS loads. Power was distributed externally to the TACS, Instrumentation, etc., and through OWS feed-throughs to redundant buses routed to an electrical power and control console. In turn, the power was routed from the console to systems/equipment and experiments internal to OWS. The console in conjunction with remote control panels contained switches, circuit breakers, and indicators to permit crew control of power distribution to end items. The EPDS received 25.5 to 30 Vdc from the AM and supplied 24 to 30 Vdc to the end items. Wiring to end items was electrically protected with circuit breakers and physically protected from damage and fire by metallic trough-shaped conduits.

g. Illumination System. An illumination system in the OWS was provided to allow for normal and emergency crew activities and experiment operations. The system consisted of general illumination lighting, initial entry and emergency lighting, and auxiliary lighting.

For general illumination, there were 42 floodlights; 18 in the forward compartment with 8 on the forward dome and 10 on the forward walls, 4 in the wardroom, 3 in the waste management compartment, 3 in the sleep compartment, and 14 in the experiment area. For redundancy, one-half the lights in each area were on Bus 1 and the remainder on Bus 2.

For initial crew entry into OWS and for emergencies, a lighting system was provided to control 8 of the 18 lights in the forward compartment. The floodlights illuminated regardless of the position of their remote or integral light switch. The initial entry lighting was controlled by a single switch in the aft compartment of the AM and the emergency lighting was enabled by the simultaneous failure of both OWS buses that automatically supplied emergency power to the initial entry and emergency light system. Two portable, high intensity lights, each containing 4 permanently installed fluorescent lamps, were supplied for special illumination.

h. Communication, Data Acquisition, and Command System. The OWS communications system provided capability for audio communication

between Skylab crewmen and between the crew and ground control. It also provided accommodations for video transmission from Skylab to ground control and the acquisition of biomedical data on the crewmen. Ten Speaker Intercom Assemblies (SIAs) were located throughout OWS and comprised the principal hardware of the system. The SIAs used two channels, either of which could be connected to a crewman's communication umbilical. Further, they included the capability for push-to-talk, push-to-transmit, and voice record selection by a crewman. Each SIA also included an audio device for C&W tones.

The OWS Data Acquisition System consisted of a portion of the SWS PCM Telemetry System, onboard displays and ground checkout support measurements. Low-level and high-level multiplexers, signal conditioning equipment, and decoders were located in the forward skirt of the OWS. Signal conditioning equipment, and decoders were located in the forward skirt of the OWS. Signal conditioning equipment for transducers installed aft on OWS were mounted in the aft skirt.

The OWS Command System provided automatic command capability for the first 7.5 hours of the mission. This was for control of tank pressures, thruster attitude control, solar array, meteoroid shield, and refrigeration system radiator shield deployment, the activation of the refrigeration system, and certain AM/ATM/MDA functions. The design used the S-IVB mainline switch selector, which received command input logic from the IU. The AM Digital Command System served as backup.

i. Caution and Warning (C&W) System. The C&W system for the OWS was an integral part of the system for Skylab. The system provided visual displays and audible tones when selected parameters would reach out-of-tolerance conditions. The parameters selected were those that could jeopardize the crew, compromise mission objectives, or, if not responded to in time, result in the loss of a system. The monitored parameters were categorized as Caution, Warning, or Emergency parameters. The system was monitored in the AM. The OWS provided redundant displays for crew scanning when they were in the experiment compartment. The OWS C&W panel was primarily a repeater station that displayed the condition of selected cluster parameters. Six emergency, two caution, and two warning parameters were displayed.

j. Habitability Support System. The OWS Habitability Support System consisted of the following subsystems.

(1) Waste Management System (WMS). The waste management collection module housed the equipment used to collect feces and urine. Feces was collected in a bag using airflow into the bag to simulate gravity. The air entered the bag, passed through a hydrophobic filter and subsequently through an odor filter and blower and was exhausted into the Waste Management Compartment (WMC). Urine was collected in a receiver and hose similar to an aircraft relief tube. A centrifugal separator separated the air from the urine. Air passed through the same odor control filter and blower as did the feces collection air and the

urine was pumped by the separator into a four liter storage bag. To obtain samples to be returned for the medical experiment, the feces were vacuum-dried in a waste processor and a urine sample of 120 ml was extracted from the storage bag and then placed in a freezer for storage. A vacuum cleaner was included in the waste management equipment. The same blower used in the collection module was used for suction. The vacuum cleaner used a bag similar in operation to the fecal bag. The trash airlock was used to dispose of trash from the cabin into the waste tank. Trash was placed in a standard disposal bag, inserted in the airlock, the lid was closed, the trash was ejected into the waste tank.

(2) Water Management System. Water was stored in ten, 600-pound capacity stainless steel tanks. The tanks contained an integral stainless steel expulsion bellows, fill and drain ports, iodine and sample ports, level indicators, and shutoff valves. The water was transferred by Teflon-lined hoses to the wardroom for drinking water and to the WMC for personal hygiene water. In both compartments, the water was heated to the desired temperature. There was also a chiller in the WMC to supply chilled water for drinking. The hot water in the wardroom was used for food reconstitution and dispensers were available for both hot and chilled water. The water in each water storage tank was initially purified by using iodine as a biocide and the purity was maintained by periodically injecting iodine in the water. A portable water tank with a 26 pound capacity was provided for contingency water supply and also to support the water network fill and flush during activation.

(3) Personal Hygiene System. Personal hygiene equipment was provided for the maintenance of health and personal cleanliness. A personal hygiene module was provided to store supplies required by the crewmen and dispensers for utility tissues, wash cloths, towels, and chemically treated cotton pads were also provided. The capability to dry wash cloths and towels was available.

(4) Body Cleansing System. Body cleansing was accomplished both by the shower and by sponging with wash cloths. A wash cloth squeezer was provided with the wash cloths. The shower contained an enclosure with a continuous airflow as a gravity substitute for moving water from the crewmen. A water bottle was filled from the WMC water dispenser and attached to the ceiling at the shower location. The water remaining after the shower was vacuumed and passed through a centrifugal air/liquid separator. The air was then filtered and pumped through a blower into the cabin.

(5) Food Management System. The food management subsystem consisted of equipment and supplies required for storage and consumption of foods. Food was stored in food boxes, galley trays, food freezers, and a food chiller. A galley, components of the food table, and food trays were provided for preparation and serving of food and chilled drinks. Food cans and beverage packs were grouped in menu form in food overcans. A heater tray was available to heat the food during preparation of the meal.

(6) Sleep Support System. Sleep restraints were provided for each crewman and they provided thermal comfort and body restraints. The sleep restraints were mounted on frames in the sleep compartments.

(7) Suit Drying System. The suit drying equipment, which consisted of a blower, hose, and desiccant bags, was provided to remove moisture from inside the pressure suits after each suited operation. Pressure suits were dried at three suit-drying stations located in the OWS forward compartment. Drying was accomplished by installing a suit in the drying station, which consisted of portable foot restraints and a hanger strap that suspended the suit between the floor and the water ring foot restraints. The blower unit forced drying air through a hose and in the suit. Moisture was dried by the air and collected by the desiccant bags. The desiccant bags were subsequently dried in the WMC waste processor.

(8) Refrigeration System. The OWS refrigeration system was a low temperature thermal control system that used Coolanol-15 as the refrigerant in a closed loop circuit. Heat was dissipated through a ground heat exchanger cooled by ground equipment during prelaunch operations and by a radiator, which was externally mounted at the aft end of OWS, for orbital operations. The system provided food freezers and chillers for food and water in support of habitability and urine freezers and chillers in support of the biomedical experiment. The system had dual coolant loops and redundant components to provide reliability and controlled temperatures through a range of plus 42°F to minus 20°F.

(9) Atmosphere Control System. The OWS, which was pressurized to 26 psia with N₂ in both the crew habitation area and waste tank for launch was vented after orbit insertion. The habitation area was then repressurized to 5 psia with O₂ to provide the desired breathing atmosphere. The circulated cabin gas was reconstituted in the AM. The ventilation ducts, each with a circulation fan cluster, routed reconstituted air to a plenum chamber located to the rear of the aft floor in the OWS for diffusion through floor diffusers into the cabin.

k. Stowage System. Stowage capability for provisions was included throughout the OWS. Twenty-five standardized stowage containers in the forward dome and 16 standard stowage lockers located in the various areas accommodated general provisions such as clothing, sleeping restraints, urine collection bags, etc. For ambient food storage, 11 containers in the forward compartment and two galley cabinets were provided. Five food freezers, three in the forward compartment and two in the wardroom were installed. A refrigerator for perishable food was located in the wardroom and a urine freezer was included in the WMC. The total stowage capability of the 210 containers onboard was 580 ft³.

1. Experiment Accommodations. For OWS experiments, hardware accommodations necessary to integrate experiment equipment and perform the experiments were provided. These consisted of structural attachments, electrical cabling, pressurization and vacuum plumbing, and stowage

restraints. A pair of scientific airlocks antisolar and solar, were installed in the cylindrical tank walls of the habitation area in the forward compartment to provide visual and physical access to the outside. The vacuum access for the waste management system was through the waste tank to use the nonpropulsive venting system of the waste tank. Vacuum provisions were provided to accommodate the metabolic activity and lower body negative pressure experiments.

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The overall performance of the OWS systems was considered exceptional throughout the Skylab missions. A major anomaly occurred during the launch of SL-1 when the Meteoroid Shield failed and resulted in the loss of Solar Array Wing Number 2 and failure of Solar Array Wing Number 1 to deploy. Additionally, this anomaly caused excessive temperatures during the initial days of the mission but no permanent damage was experienced by critical systems. Successful deployment of the JSC parasol (sun shade) relieved the high temperature condition and subsequent deployment of Solar Array Wing Number 1 normalized the power capability sufficiently to allow near nominal mission performance. No other functional system failures were caused by the loss of the Meteoroid Shield. Minor anomalies were experienced in the Experiment Accommodations System but were not considered significant and were overcome through workaround procedures.

4. Apollo Telescope Mount. The ATM was designed and developed as an inhouse center responsibility. The primary function of the ATM through its experiments was to provide high resolution data of the entire solar disk, corona, and other features of interest. Refer to Figure I.G-4 for general ATM configuration. Additionally, other prime functions of the ATM were to provide approximately one-half of the electrical power for the SWS using the SAS and to provide attitude control and stabilization for the orbital assembly. Major system elements of the ATM are summarized as follows:

a. Structure and Mechanical System. The ATM Structure and Mechanical system provided for the mounting of all ATM equipment and the ATM experiment canister and the means of mounting the ATM to the rigidizing frame. The rigidizing frame was mounted to the ATM-DA, which deployed the ATM in orbit. It also provided the mechanisms to unlock and fine point the canister, operate the canister sun shield aperture doors, unlock the film retrieval doors, and finally, it provided mechanical aids for astronaut EVA.

b. Thermal Control System. The ATM TCS was designed to maintain all temperature sensitive hardware, which included electromagnetic equipment and experiments, within an acceptable temperature range throughout the Skylab mission by assuring that an acceptable thermal balance was maintained between waste heat dissipation and the varying space environment. Two types of thermal control techniques were used. Passive thermal control management consisting of insulation, low-conductance mounts,

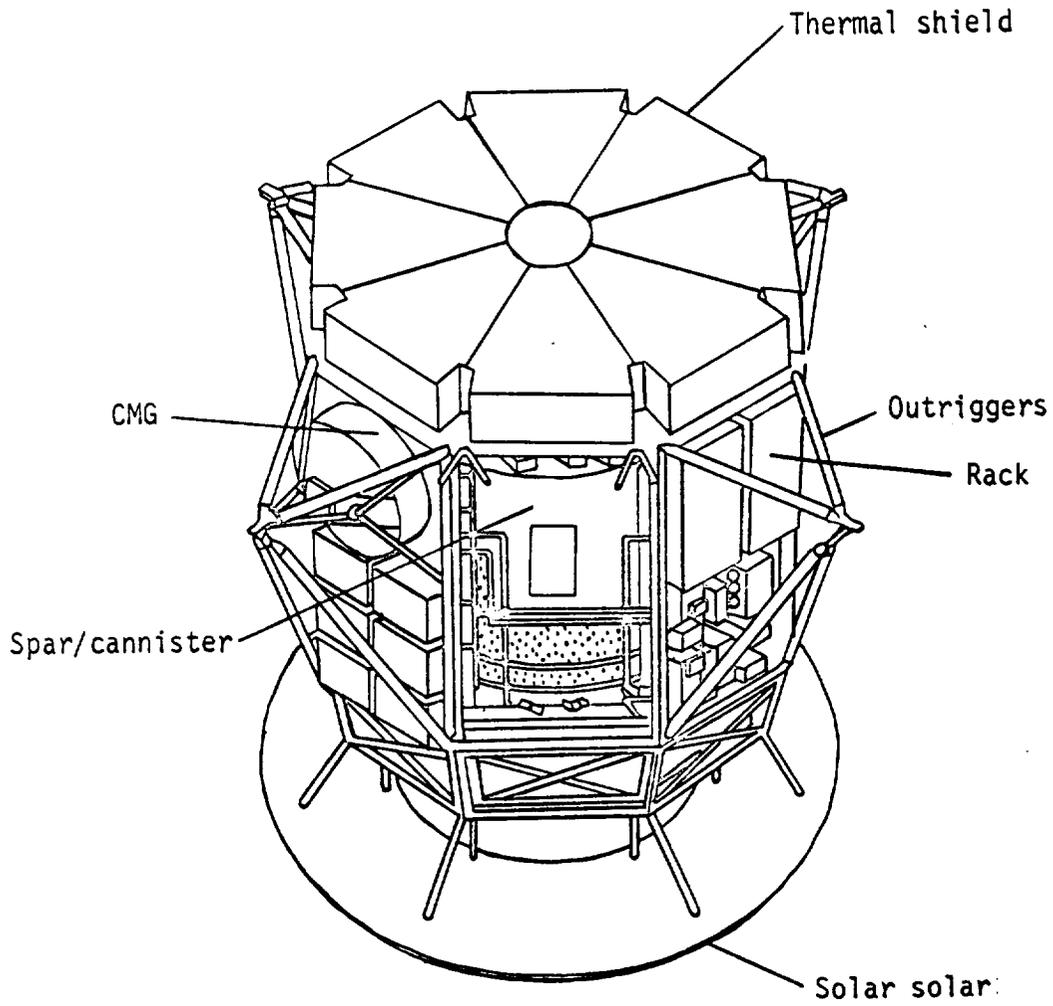


Figure I.G-4 Apollo Telescope Mount

reflective/nonreflective surface coatings and thermostatically controlled heaters were used for rack mounted equipment that generally had broad allowable temperature bands. An active TCS consisting of coolant fluid and associated pumps, radiators, and controls was required for the experiment canister to eliminate experiment temperature fluctuations and gradients that would adversely affect the scientific data. In addition, individual experiment heaters, canister and spar insulation and surface coatings contributed to the canister thermal control.

c. Electrical Power and Network System. The ATM electrical power and networks system was a combination of the ATM SAS, 18 charger/battery/regulator modules (CBRMs), transfer buses, switch selectors and power, control, measuring, and logic distributors. The transfer buses were designed to transfer power from the ATM to the rest of the cluster, as required to meet the overall requirements of the cluster. The ATM power system could be operated independently or in parallel with the OWS/AM power system, which produced a sharing capability of 2500 watts in either direction.

d. Electrical Power System (Solar Array). The ATM Solar Array consisted essentially of 18 independent photovoltaic power generating systems (solar panels) divided among four wing assemblies. Each wing contained four full panels and one half panel. Each panel contained 20 solar cell modules and was capable of supplying its respective CBRM 580 watts. Each solar cell module contained either 684 type A cells, or 228 type B cells. The ATM solar wings, when deployed, were locked within five degrees of a plane perpendicular to the ATM main axis. The solar array was comprised of two major sections, the electrical (power generating) section and the mechanical (structural and deployment) section.

The solar wing cinching system and wing deployment system were essentially one-time operational systems with the primary purpose of deploying the wings from the folded cinched launch configuration to the deployed orbital configuration.

The solar wing mounting structures provided the basic support for the entire wing assembly and were the interface to the ATM rack. The inboard half panel interfaced with the mounting structure through five hinge points at the ATM sun end, and the inboard scissors arms interfaced with the mounting structure through two sliders and tracks. The wing assembly five solar panels were tightly cinched against the mounting structure forming an integral package that could be handled and transported independently of other ATM hardware.

e. Instrumentation and Communication (I&C) System. The ATM I&C System was designed to perform ATM data processing and transmission, provide command control of ATM Subsystems and experiments, and aid in experiment operations and pointing for solar data acquisition. This system consisted of the following subsystems:

- ATM data subsystem

- ATM DCS
- ATM TV subsystem

f. Attitude and Pointing Control System (APCS). The APCS was designed to provide three-axis attitude stabilization in the required operational attitudes, to ensure controlled operational maneuvers of the Skylab and to provide pointing control in support of the ATM experiments.

A CMG system and a TACS (see paragraph I.G.3.d) provided the torques necessary for attitude control and maneuvering of the Skylab. The TACS was used to assist the CMG when the Skylab attitude control or maneuvering requirements exceeded the CMG momentum storage capacity and for the purpose of desaturating the CMG when the CMG stored momentum was at or near maximum capacity.

The APCS was designed for two basic modes of operation: solar inertial (SI) and Z-local vertical (Z-LV). All other attitude modes were attained by maneuvering or offsetting from the two basic attitudes.

g. Control and Display System. The ATM C&D Console was a rack-mounted console that provided a man-machine interface for the operation and monitoring of the ATM systems. The console consisted of nine panel assemblies, each of which contained various C&D sections. The panel assemblies were comprised of the ATM experiments and supporting systems. Commands to the ATM systems were provided by toggle and rotary switches, the Manual Pointing Controller, and the DAS. All critical switch functions were redundantly wired or were redundantly available through the DAS. Monitoring of system parameters was accomplished by the use of status lights, meter confidence lights, alert lights, dual scale vertical meters, time-shared digital displays, and TV displays. Controls were available for power distribution, overload protection, lamp testing, parametric selection, and console lighting.

Coolant control for the C&D console was provided by a liquid water coolant loop. The system was designed to reduce and maintain average console temperatures at approximately 85°F and operate at a maximum loop pressure drop of 3.0 psi at 220 lbm/hour flow. The coolant loop was an open cycle cold rail system, fluid being supplied externally by the AM coolant system. Coldrails were structurally integrated in the console structure. The console frame served as an intermediate heat sink, transferring component heat loads to the coolant loop for removal from the console.

Equipment ancillary to the C&D console consisted of an I/LCA, a Backup Inverter-Lighting Control Assembly (BI-LCA) System, an EVA Canister Rotation Control Panel, and a DAS Backup Panel.

- h. ATM Experiments

(1) ATM Experiment S052. Experiment S052, White Light Coronagraph was an externally occulted white light coronagraph designed to block out the image of the sun's disk and take white light pictures of the solar corona in the visible region of the electromagnetic spectrum centered about 5400 A.

The experiment's TV camera allowed the astronaut to make visual observations of the corona that aided in the determination of the most opportune times to obtain photographs using the film camera.

(2) ATM Experiment S054. Experiment S054, X-Ray Spectrographic Telescope was a slitless spectrograph consisting of grazing incidence telescope and a transmission grating, designed to obtain X-ray images, spectra, digital intensity data, and white light image of the entire solar disk.

(3) ATM Experiment S055A. Experiment S055A, Extreme Ultra-Violet (XUV) Scanning Polychromator/Spectroheliometer was an XUV multi-channel photoelectric spectroheliometer, designed to obtain XUV images and spectra of small portions of the solar disk.

(4) ATM Experiment S056. Experiment S056, X-Ray Telescope was a grazing incidence X-ray telescope with pulse height analyzer, designed to obtain X-ray filter images of the solar disk and digital data at 10 predetermined wavelength bands simultaneously.

(5) ATM Experiment S082A. Experiment S082A, XUV Spectroheliograph was a slitless XUV spectroheliograph, designed to obtain a row of overlapping XUV images of full solar disk, each representing a different wavelength.

(6) ATM Experiment S082B. Experiment S082B, XUV Spectrograph was an XUV spectrograph designed to obtain images of XUV spectra lines, white light images of small portions of solar disk, and XUV image of entire solar disk.

The XUV monitor provided a real-time image of the solar disk in the wavelengths from 170 to 550 Angstrom Units (A) and pointed the spectrograph to solar units of interest.

(7) ATM Experiments Hydrogen-Alpha 1 and Alpha 2. The Hydrogen-Alpha 1 was a telecentric Cassegrain telescope, designed to obtain a 4.5 to 15.8 arc minute diameter of the H- α solar image. The telescope's vidicon camera provided a visual display of the sun to the astronauts, and its film camera recorded where the other instruments were pointing throughout the mission.

The Hydrogen-Alpha 2 was a telecentric Cassegrain telescope, designed to obtain a 7 to 35 arc minute diameter H- α solar image. The telescope's vidicon camera provided the astronaut with a visual display of the sun.

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The ATM on Skylab provided data that indicated the performance of the ATM, its experiments, the supporting systems, and the crew, had met or exceeded the premission objectives. This conclusion is based on Skylab mission performance and the evaluation of the systems and experiment data. The excellence of the ATM ground performance during the critical early mission period provided ground personnel with the time and capability to effect the changes required to continue the Skylab mission.

Due to the management of the ATM systems, workarounds and redundancy designed into the ATM systems, anomalies encountered during the Skylab mission had no appreciable impact on the ability of the ATM to support the mission objectives.

The ATM instruments exhibited outstanding performance throughout the entire Skylab mission. No major hardware problems occurred that significantly impacted the operation of a single instrument. The outstanding performance of the instruments was substantiated by comments from the Principal Investigators regarding the excellent quality of the scientific data returned. Resolutions approximating one arc-second were attained on much of the solar imagery.

5. Payload Shroud. The PS was designed to provide an environmental shield and aerodynamic fairing for the SWS forward of the FAS portion of the AM, and was designed to support the ATM during prelaunch, launch, and boost phases. The PS provided a noncontaminating separation system that would jettison the PS from the Skylab Cluster during orbit.

General design features of the PS included the following major system elements: Biconical nose and a 22-foot diameter aluminum cylinder shell structure, separation system including the discrete latch system and the longitudinal thrusting joint systems, electrical/ordnance system, instrumentation system, and nose cone purge duct system.

An all-aluminum, ring-stiffened, semimonocoque shell was selected for the PS basic structure. The skin-thickness/ring-spacing parameters were optimized to provide adequate strength, and provide the required acoustical attenuation without need for special attenuation coatings.

A quad section radial separation approach was selected. A noncontaminating longitudinal thrusting joint device was selected for the separation system. Discrete latches were needed for structural ties across the two major ring frames: The PS base ring and the non-cylinder intersection ring. Linear explosive devices were selected to provide the power to actuate both the thrusting joint system and discrete latch system. A Saturn-qualified electronics bridge wire system was selected for the electrical/ordnance system.

A slide-off disconnect base attachment system was used; the PS quad-section motions during the jettison event automatically disengage the PS from the Airlock FAS. Lanyard electrical umbilicals, PS to FAS, automatically disconnected during the jettison event.

The PS was designed to structurally support the ATM during ground operations and during flight prior to the PS jettison event. The ATM structural support connection was designed such that the ATM outrigger support points were automatically released by PS quad-section motions during the jettison event. Refer to paragraph II.E.2.a for PS illustrative description.

6. Experiment Integration. The successful integration of experiments in Skylab represented a major task of the center. The MSFC experiment responsibility was two-fold: (1) the development of 51 MSFC corollary experiments from a conceptual phase through the delivery of hardware and their ultimate integration in Skylab modules, and (2) the integration of 29 JSC-supplied experiments in Skylab modules. Basically, the integration responsibility included identification and analysis of requirements, provisioning of facilities, assessment of compatibility with Skylab systems, physical installation, and integration of test and checkout requirements.

The successful implementation of the experiment program in Skylab was demonstrated by the overall success of operation during the three Skylab missions. More total experiment performances were accomplished than had been envisioned in premission planning. Observations of comet Kohoutek and additional science demonstrations were conceived and implemented during the missions.

7. Crew Systems. The significance of man on the total Skylab program is one of extreme importance. System hardware performance is enhanced and program objectives are guaranteed achievement when operators who have the ability to think and reason, perform scheduled and unscheduled inflight maintenance, and provide system adjustments as required are an integral planned part of the program.

The role of man throughout the Skylab program provided the necessary insight to assure that man/system interfaces were compatible and practical. From the inception of hardware design concepts, crew system reviews were conducted through all phases of hardware development, system buildup, testing and finally as an operational system. The accumulative effect of the NASA and contractor crew system personnel together with the astronauts influence on the Skylab cluster design was in totality an exceedingly significant contribution. When the crew system design changes are considered individually, it is difficult to conclude that any single change made an appreciable difference between success or failure of a specific mission task. However, the accumulative inputs increased the "workability" of the Skylab, saved time in task performance and most importantly gave the astronauts the interior arrangement and man/system interfaces necessary to mission success.

Both formal and informal means of implementing desired design changes were accomplished through the issuance of a RID.

Formal action was taken on the requested action by established decision making review boards. Informally, requested changes from the flight crew or their representatives was implemented if it was a minor change that did not affect the program schedule, was not a significant cost increase, and did not adversely affect inflight task performance time. An example of a significant design change requested by the flight crew was the relocation of the ATM C&D console in the MDA interface.

The flexibility and value of man as part of the system, with technical and planning support from crew system personnel on the ground, was emphasized during the mission with the successful release of an OWS solar wing and the deployment of a sun shield to offset problems caused by an anomaly during launch. These efforts were instrumental in normalizing electrical power capabilities and temperatures and allowing the continuation of the mission. Another graphic example of the total teamwork concept of crew and ground support organizations such as operations, scientists, and contractors, was the rapid response to the advent of the comet Kohoutek. The comet was detected during the unmanned period between SL-3 and SL-4. The SL-4 crew was briefed, trained, special comet experiments provided, flight plans extensively revised and a successful program conducted. All this was accomplished in a matter of days by concerted team effort.

The ultimate objective of determining man's capability to survive and function during extended periods of time in space was demonstrated successfully and provides assurance that future manned space programs can succeed.

8. Systems Engineering and Integration. The overall integration of Skylab hardware was a responsibility of MSFC and involved extensive coordination activities with the JSC, KSC, and the many Skylab contractors. MSFC management effectively used the technical expertise provided by systems engineering personnel to assure that the integration of all requirements was accomplished in a timely and technically acceptable manner. This effort involved engaging the flight crews in the design reviews and testing of hardware having direct crew interfaces and utilizing to the fullest the crew expertise on man/machine relationships. Flight Operations personnel were also involved to the greatest extent possible to assure compatibility between the systems and Flight Operations planning and interfaces.

Techniques that were successfully employed included technical trade-offs to establish the feasibility of Skylab configurations particularly in support of the decision to convert to the dry workshop. Extensive use of technical teams organized as panel and subpanel working groups were instrumental in establishing and controlling requirements throughout the program. The compatibility of hardware versus requirements was effectively analyzed and implemented through scheduled and special reviews using systems engineering personnel from the inception of design requirements through FRRs. Control of functional and physical interfaces through

formal documentation required a systems overview to assure compatibility of interfacing Skylab systems. Formal configuration control of program baseline documentation was technically managed by systems engineering and provided technical impact assessment and compatibility review in support of program management.

The significance of effective systems engineering and integration efforts is best summarized by the timely identification and resolution of program problems on a continuing basis throughout Skylab development.

H. Conclusions

The successful Skylab program marked the end of the first era of manned spaceflight and laid the foundations of an expanded role for the future of man in space exploration. Skylab ended the era in which both the United States and USSR space programs sought to determine the limits of man's useful performance in a space environment. Skylab answered affirmatively the questions of man's ability to adapt to a space environment and the value of his contributions to space operations. It also laid the foundations for future space operations by demonstrating the basic feasibility of shuttle operations and the habitability and workability of large long-duration space stations.

The most important contribution is the convincing manner in which Skylab proved man's ability to adapt to long periods of space flight without losing his normal capability to work effectively over a broad spectrum of space laboratory activities. These ranged from the solar panel and solar shield external repairs to a wide variety of internal equipment and scientific experiment fixes that enabled the three Skylab missions to exceed all of their prescribed workload parameters by wide margins.

II. Saturn Workshop Systems

SECTION II. SATURN WORKSHOP SYSTEMS

A. Systems Approach

1. General. Systems Engineering and Integration (SE&I) played a vital role in the successful achievement of Skylab Program objectives. No previous program was as complex from a technical standpoint nor involved so many contractor efforts to produce an effective end product. The need for system integration was formally recognized as early as May 1966, when study contracts for Apollo Applications Program (AAP) experiment integration were awarded.

In July 1967 a contract for payload integration of experiments and experimental support equipment on Apollo Applications spacecraft was awarded to the Martin Marietta Corporation (MMC). In addition to work involving the OWS and the ATM, integration of JSC experiments and test integration planning and support for launch operations at KSC were included.

From the time that AAP became a formal program in December 1965 through the decision to convert from a "wet" to "dry" workshop concept in July 1969, the SE&I activities were primarily involved in study efforts to establish program requirements, mission configurations, and trade-offs on conceptual flight systems and system requirements. Additionally, attention was directed to the definition and integration of experiment requirements for the AAP payloads. Evaluation of testing requirements was somewhat low key during this period for total systems had not been defined.

With the July 1969 decision to convert to Dry Workshop, SE&I efforts were immediately directed towards preparation and release of the Cluster Requirements Specification, RS003M00003. This document resulted from a joint MSFC/JSC effort and represented the first formal release of system level requirements. It provided a common baseline controlled through level 2 (intercenter) change control and served as a baseline for CEI Specifications, ICDs, and associated performance criteria to assure a common development base. The decision to convert to the Dry Workshop was based on a significant systems engineering effort, which culminated in a formalized document entitled "Technical Considerations, Saturn V Workshop Program Definition Study." The technical trade-off and feasibility study results included in the document provided the necessary decision-making criteria for program management.

During the hardware development phase that followed the Dry Workshop decision, SE&I participated in PDRs and CDRs to assure the compatibility of baseline hardware with overall system requirements. With

the integration of total hardware in the Saturn Workshop (SWS) modules, SWS module build-up and ultimately a total SWS, reviews were expanded to higher managerial levels. The SE&I assisted program management with the technical aspects that resulted in meaningful, standardized reviews and established a confidence level that mission objectives could be successfully accomplished.

Acceptance Reviews, Design Certification Reviews (DCRs), SOCARs, Hardware Integrity Reviews (HIRs), and Flight Readiness Reviews (FRRs) were the significant technical reviews that involved SE&I support to program management. These efforts were reflected in the overall success of the Skylab missions.

The previous paragraphs relate the more significant areas of SE&I participation. The following paragraphs discuss in more detail the areas that involve system engineering and are considered critical in the development of a successful Saturn Workshop and involve the type of activity considered pertinent on future programs.

2. Conceptual Phase. The conceptual phase of the AAP/Skylab Program encompassed the time frame between official program start (December 1965) through the decision to convert from a "wet" to a "dry" workshop (July 1969). The role of systems engineering during this conceptual phase centered around analysis of mission objectives (for the various missions identified) in sufficient detail to develop concepts of implementation. Activities during this phase included feasibility studies and development of system requirements documents and specifications and first-order system schedules and costs. A significant SE&I contribution was realized in the dry workshop decision and associated integration of payload requirements as follows:

a. Dry Workshop Concept. The center initiated conceptual studies in October 1968 that involved the substitution of the "dry" for the "wet" workshop program. The basic concept was proposed as a standby Saturn IVB (S-IVB) stage stripped of existing hardware and one substitute standby for the wet S-IVB.

b. Payload Integration and System Engineering. A letter contract was definitized between the center and the MMC for the Payload Integration and Systems Engineering effort required to support center responsibilities. The contract was awarded in January 1969 and reflected the center's emphasis on strong systems engineering management.

c. Dry Workshop Decision. In July 1969 it was decided to convert from a "wet" workshop to a "dry" workshop concept. This decision was announced by NASA Administrator, Dr. Thomas O. Paine, and reflected the MSFC position as documented in a report entitled "Technical Considerations, S-V Workshop Program Definition Study." The report was the result of a strong system engineering effort that involved conceptual design and feasibility studies to determine the advantages/

disadvantages of converting to the "dry" workshop concept. The study recommended the "dry" workshop concept and significant advantages were identified as follows:

(1) Total Payload Package. Simplification of the total space vehicle by integration of systems into a total payload package, outfitted and checked out on the ground.

(2) Reliability. Increased reliability because of simplification of hardware and astronaut operations.

(3) Earlier Experiments. Operation of experiments in an earlier time frame with the improved probability of achieving mission success.

(4) Cost Reduction. Potential reductions in total program cost due to hardware simplification.

d. Hardware Simplification. Primary hardware simplification included the following:

(1) Propulsion. Eliminating the propulsive features of S-IVB stage.

(2) Solar-inertial Attitude. Eliminating major in-orbit pointing maneuvers by use of a solar-inertial attitude in all phases of the mission.

(3) Interface Reductions. Reducing the interface functions between the cluster and the CSM, which is mainly a ferry vehicle for the crew.

(4) Ground Outfitting. Outfitting the workshop on the ground, which allows complete assurance that everything is in working order before launch and also reduces astronaut operations and requirements on the hardware to establish habitable crew quarters.

(5) Resupply Reduction. Reducing resupply and logistics requirements by loading consumables and expendables into the S-V Workshop (WS) before launch.

(6) Quiescent Command and Service Module (CSM). Minimizing the hardware modifications required on the CSM by maintaining it in a quiescent stage during docked operations.

The probability of achieving total mission success was improved by the requirement for fewer launches; elimination of the Lunar Module (LM); elimination of propulsion, passivation, and activation functions required by the Wet Workshop; earlier achievement of experiment and program objectives; and ability to check out most systems and experiments in their operating modes on the ground.

During the several years encompassing the conceptual phase of the program, many iterations were involved. The role of systems engineering was considered of prime significance in the decision-making process and culminated with a strong effort that supported the final decision to proceed with the "dry" workshop concept.

3. Definition Phase. This phase of the AAP (Skylab) Program consisted of the detailed definition of the total system including flight hardware, support equipment, software and personnel. The phase essentially began with the decision to convert to the "dry" workshop. Products of this phase included development of cluster requirements, operational definitions, more detailed trade studies, configuration descriptions and preliminary hardware specifications.

The CRS was released during mid-1969 and was considered as the single authority and baseline for all integrated system level design, build, test, and performance requirements. The document was developed through a joint MSFC/JSC effort and provided a single, viable working document for all contractors and NASA centers to use. The implementation of this specification and a subsequent baseline through the Level 2 Configuration Control Board (CCB) provided a controlling document for development of CEI Specifications, ICDs, and associated performance criteria to assure fully integrated systems, compatible with mission objectives.

4. Design Phase. The design phase of the program consisted of the detail design and fabrication of each system element, evaluation of the system through analysis and test, activation of the system, and all other related activities required to support and use the system. The complexity of the program, together with the involvement of many contractors, necessitated rigid system level control to assure physical compatibility of interfacing hardware, functional compatibility at the system level, and maximum confidence that mission objectives would be met both operationally and as a man-machine interface.

During the design phase, the overall complexity of the program became extremely critical from the standpoint of providing effective controls and integration of requirements into a total Skylab system. With a multitude of contractors providing many hardware elements, program management recognized the need for an effective use of SE&I. The primary areas of concentration that required System Engineering expertise included interface requirements, configuration control, key hardware milestone reviews, compatibility assessment reviews, special reviews, system verification, and special analysis.

a. Interface Requirements. The tremendous complexity of Skylab interfaces, with the dispersion of development and production activities across the country, demanded accurately defined and tightly controlled interfaces. It was soon learned that third-party custodianship of ICD's could not accomplish this task in a timely manner. Interface Control Documents between modules were defined after detailed

system requirement ICDs had been agreed to between centers. Systems ICDs were necessary where significant portions of the hardware were supplied by more than one center. The systems level ICDs also proved to be an effective way of performing a systems engineering evaluation of changes late in the program and served as catalysts to initiate compatibility testing between the ground and airborne systems. Maintenance was assigned to one party of the interface, under CCB management. Interface Control Document changes were coordinated with all other affected interfaces by the responsible party. Contractual requirements ensured that this work and related engineering change processing was accomplished expeditiously with management visibility.

b. Configuration Control. Comprehensive configuration management, implemented early, is essential for any program, and particularly for one with complex interfaces and a variety of hardware and documentation sources.

Configuration management and change integration for the SWS was a responsibility of the systems engineering and integration activity at MSFC. A change integration group was established early in the program to develop necessary guidelines and support all Level 2 and 3 CCB activities.

The system used by the Saturn program was successfully modified and implemented for the SWS program. The system called for the assignment of a single program control number (PCN) and a responsible change integration engineer to each change. A computerized tracking and accounting system which was also developed for the Saturn program, became the working tool of the group. The system provided daily reports on the status of changes, pointed out delinquencies, and identified all affected interfaces and modification kit status once hardware was delivered.

An intercenter Change Integration Working Group (CIWG) was established to coordinate hardware design changes occurring early in the program. This group acted as a Level 2 preboard to screen all changes and provide current status for total change activity that affected SWS module interfaces, ground systems, and crew operations. A SWS Change Review Board (CRB) was implemented locally and this MSFC board met daily to review all new change requests and the progress of all changes being worked at the center.

The following observations are made based on experience gained in the SWS change integration activity.

(1) Change Control. Assignment of a single program-wide tracking number and one responsible change integration engineer to each change is an absolute necessity in a complex program having many changes affecting many interfaces. This "cradle-to-grave" concept for change tracking and integration responsibility ensured positive identification

and coordination between all involved centers, contractors, projects, and contract personnel.

(2) Change Integration Working Group. The SWS CIWG was made up of representatives of the various technical systems disciplines and systems engineering and integration. Such a group proved to be a primary tool for ensuring that early design was well coordinated. This group must be established early and represent all involved centers and hardware contractors.

(3) Change Review Board. This daily review board ensured that changes were being worked effectively and expeditiously with all affected program elements. The board chairman should have Level 2 signature authority and each Level 3 organization should be represented on the board by signature authority.

(4) Configuration Control Boards. The SWS Level 2 CCB was a primary function of the systems engineering and integration activity. Representatives of that group also sat on Level 3 boards to ensure proper coordination of changes at Level 2 and at other Level 3 boards. Requirements should be established for each Board, regardless of level, to convene on at least a weekly basis. Attendance discipline is mandatory for successful board operation. Alternate members must be prepared to function responsibly when principal members are absent. Working changes outside a board meeting causes delays in dispositioning and issuing direction to contractors. It would be beneficial to issue uniform direction to suppliers, especially when interfaces are involved. Configuration Control Board Directive forms used by NASA vary, and a standard form would aid recipient contractors in complying with given direction regardless of the NASA source. The MSFC Directive form and procedures for completion are recommended.

(5) Intercenter Subagreements. Early development and implementation of change integration subagreements between centers is necessary to ensure that a closed loop system exists for identifying, coordinating, and tracking changes that affect more than one center. Necessary contractual direction must also be imposed as required to ensure implementation of these subagreements.

(6) Coordination, Tracking, and Accounting. It should be recognized that an established, well-organized change integration group, which has acquired and developed the fundamental skills and tools for coordinating and tracking complex systems changes, is a natural source of similar support in other systems engineering and integration activities. The SWS change integration group, for example, was used to coordinate and perform program tracking and accounting in the following areas:

(a) ICD change status and indexing.

- (b) Work remaining to be done in-plant, and work deferred to KSC.
- (c) Crew procedure change status and coordination.
- (d) Test change notice status and coordination.
- (e) Program documentation status and change coordination.
- (f) Levels 2 and 3 CCB secretarial functions.

c. Key Hardware Milestone Reviews. The Skylab Program implemented the key hardware milestone reviews (preliminary requirements, preliminary design, critical design, design certification, acceptance) as accomplished on previous programs. These reviews were on an end item or module basis; however, due to the modular construction of Skylab, end-to-end system reviews were required to ensure that the totally integrated system would satisfy mission requirements. To accomplish this, a cluster system review was instituted before the module CDRs to ensure total system requirements were complete and being implemented. The CRS was the foundation for this review. Additionally, module level DCRs were conducted and served as inputs to the overall systems level DCR. The foundation for certification of the cluster systems was the results of the KSC integrated systems tests.

The module and cluster system reviews were structured by system representatives from the Science and Engineering (S&E) technical disciplines. The Program Office co-chaired or chaired the individual system review sessions.

Skylab experience has demonstrated that an effective design review must not only emphasize the hardware, but should also include the review of inflight repair possibilities, single failure points, critical mechanisms, test plans, and test results. The reviews must be scheduled in a timely manner with data packages being reviewed by the pertinent disciplines before the actual review. Action items from the reviews were documented on RID forms. Post review followup and ultimate disposition of all RIDs was formalized and reported regularly. High fidelity mockups have proved to be useful for these reviews, and the importance of early availability of interface control documentation was clearly shown. Not only design personnel, but test and operations representatives should participate in design reviews.

Flight Readiness Reviews were held at the module, cluster, and mission levels. These reviews emphasized the total readiness of a particular configuration for flight. This system was used successfully on the Apollo Program and was of particular importance in determining successful operation of cluster systems. Problems or concerns identified in FRRs were given maximum attention by program management

and heavily involved systems engineering from a technical evaluation and recommendation viewpoint.

d. Compatibility Assessment Review. The SOGAR served as a mechanism for establishing dialogue and working relationships between the design, development, test, and integration and the operations personnel; facilitating a smooth transfer of pertinent data such as hardware descriptions, performance characteristics, operational requirements, constraints, mission rules, and test history. Review and revision of the mission plans, procedures, and documentation advanced the operational readiness of Skylab significantly.

The SOGAR was conducted at the center level and provided program management with the first significant data relative to the overall integration and compatibility of program requirements on an implementation basis. Extensive technical review of all program requirements as a function of a complete SWS entity and mission requirements was a responsibility of Systems Engineering and resulted in a high confidence level that total mission requirements could be met. In essence, the SOGAR acted as a forcing function in bringing all elements of the program into the proper perspective.

e. Special Reviews. The concept of review by "new eyes" was extensively used. The reviews ranged from a systems review team headed by the Deputy Associate Administrator to in-plant reviews of subtier suppliers of critical items by teams composed of specialists from MSFC and the prime contractors. Critical mechanisms were reviewed by an intercenter group of senior managerial and technical personnel. Engineering walkaround of the flight modules were patterned after the Apollo practice of bringing to bear the experience of senior NASA individuals who had no direct hardware managerial responsibility.

A comprehensive HIR by teams of MSFC specialists validated the contractor's systems of translating requirements for SWS activation sequence to flight hardware. The teams' activities were audited by a blue ribbon committee chaired from the laboratory director level. Although a great deal of time was required for the preparation and execution of these reviews, there is no doubt that they contributed greatly to the overall success of the program.

f. System Verification. The Skylab Program TCRSDs were developed in a "building block" concept. The TCRSD was developed for the modules to verify system operation in accordance with the Module End Item Specification. Additionally, experiment checkout requirements for on-module testing were included. These TCRSDs were the basis for checkout procedures and factory acceptance testing. Such documents are invaluable in establishing contractual compliance.

An integrated cluster systems TCRSD was developed to define the test and checkout requirements for the integrated Skylab cluster systems at the launch facility. This was accomplished by the formulation of cluster systems test requirements review teams composed of technical

experts from the NASA design organizations, systems engineering organizations, program offices, KSC test offices and contractors. On technical agreement by each of the system teams, the integrated TCRSD and the module TCRSDs were baselined and controlled by the Level 2 CCB. These baselined TCRSDs provided the technical basis for the final test and checkout plans and procedures at KSC.

On delivery of the modules from the factory to KSC, representatives from each of the system teams (both NASA and contractor) were assigned to KSC to maintain the TCRSDs. Required changes to the TCRSDs were implemented and controlled by the "test change notice" system that was controlled and approved by the Level 2 CCB at KSC. These teams and the Test Change Notice (TCN) board responded to the KSC test schedules.

g. Special Analysis. The complexity of the Skylab Program yielded many special problems and required the technical expertise of specialized personnel. Systems engineering evaluation of the various Skylab systems determined the need for analysis efforts in specific areas. The following paragraphs are considered significant enough for the benefit of future programs. Other analysis efforts were conducted and are identified in future sections.

(1) Sneak Circuit Analysis. Sneak circuit analysis were performed on systems to assure a high probability of freedom from unwanted current paths. Details of the analysis as performed on the Skylab Program are detailed in Section II.F. This program yielded the following results:

- (a) Identified 44 sneak circuits.
- (b) Identified a number of components that were not necessary for circuit operation.
- (c) Identified errors in documentation.
- (d) Verified electrical interfaces within and between modules.
- (e) Key source for verification of operational documentation (operational handbooks, schematics, and crew procedures).
- (f) Provided a valuable tool for investigating real-time operational problems and workaround.

(2) Corona. Early development of corona suppression specifications that define pressure and voltage potential criteria can preclude many post-design problems. Details of the corona analysis on the Skylab Program may be found in Section II.D.3.

(3) Electromagnetic Compatibility (EMC). Electromagnetic interference was not a problem with Skylab electronic devices. This was achieved by comprehensive component level testing, module system testing, and total assembled system testing.

Early identification of EMC requirements in the hardware design and generation of a module EMC control plan gave Skylab a basis for testing to verify compatibility. An EMC control group rigorously reviewed all waivers, test results, redesigns, and retest results associated with EMC.

(4) Skylab Mission Contingency Analysis. Pre-mission contingency analysis can enhance real-time response to emergencies, even if the precise contingency has not been analyzed.

Certain anomalies and contingencies that occurred during the Skylab 1 (SL-1) unmanned activation sequence were analyzed pre-mission. These analyses permitted rapid and accurate mission recovery action. Additional details on the above analyses are provided in Section II. D.1.

5. Summary. The ultimate success demonstrated by the Skylab Program is the best indicator of the total effort involved. The role of System Engineering in achieving this success is also best measured by the final product performance. Specifically, with the total magnitude of hardware elements, numerous contractor involvement, and multi-NASA center participation. The technical integration of total program requirements that evolved from the conceptual phase and proceeding through the definition, design, and mission performance phases is considered the most vital contribution by the Systems Engineering division. The most significant recommendation for future programs in the Systems Engineering area would be increased responsibility in this integration role to assure more timely identification and implementation of critical requirements.

B. Configuration Management

1. Objectives and Methodology. Past experience in undertaking large complex development programs such as Skylab has proven that effective means of control is required over the total product engineering, development, and procurement activities within the program. This control is necessary to accurately define the identity and completion status of the final product. Effective application of established configuration management concepts, proven on previous DOD and NASA programs, provided a successful method that would accurately define all Skylab end items at any point in time. Accurate definition of these end items enables program management to establish schedules, develop realistic budget requirements, and accomplish effective change control throughout the life of the program.

The first objective of the Configuration Management effort was to establish baselines to serve as a reference for controlling subsequent performance and design changes. Once these baselines were defined, changes in requirements could be formally approved with assurance that adequate consideration had been given to program impact with respect to contract costs, schedules, and incentives, as well as mission capability. Figure II.B-1 identifies the Skylab flow with respect to Skylab program phasing, and the types of changes required to each. Because of the nature of the Skylab program development, baselines were not provided for all elements at one specific time (such as end-of-the-design phase), but were completed in an incremental manner as specific end items were developed. A major configuration management task was to identify the technical documentation defining the approved configuration of the system or end item throughout the period when hardware/software was acquired. Based on the design reviews performed, a baseline for a given end item was established and the specific documentation constituting that baseline recorded. The configuration of the end item at any later date was traceable from the original baseline configuration plus all the ensuing changes approved and incorporated since that time. Therefore, the configuration of an end item was known, controlled, and thoroughly documented at any given point in time.

The control of changes to Skylab performance and design baselines was achieved through use of the multilevel CCB system shown in Figure II.B-2. Five levels of control were established, each of which had specific criteria for submitting changes to the next higher level for approval. Authority of the OMSF Level I CCB, and the Level II CCBs (formed within each center) were established in NASA Handbook (NHB) 8040.1 issued in October 1969. Types of changes within the authority of subordinate CCBs were defined in the respective center configuration management plans. Additional requirements for submittal of changes to OMSF Level I CCB and to the center CCBs were added from time to time by OMSF directives. All changes to established Skylab baselines were submitted for approval to the appropriate CCB responsible for configuration control. The CCB decision was recorded by means of a CCB Directive, upon which the contracting officer issued the contractual authority for

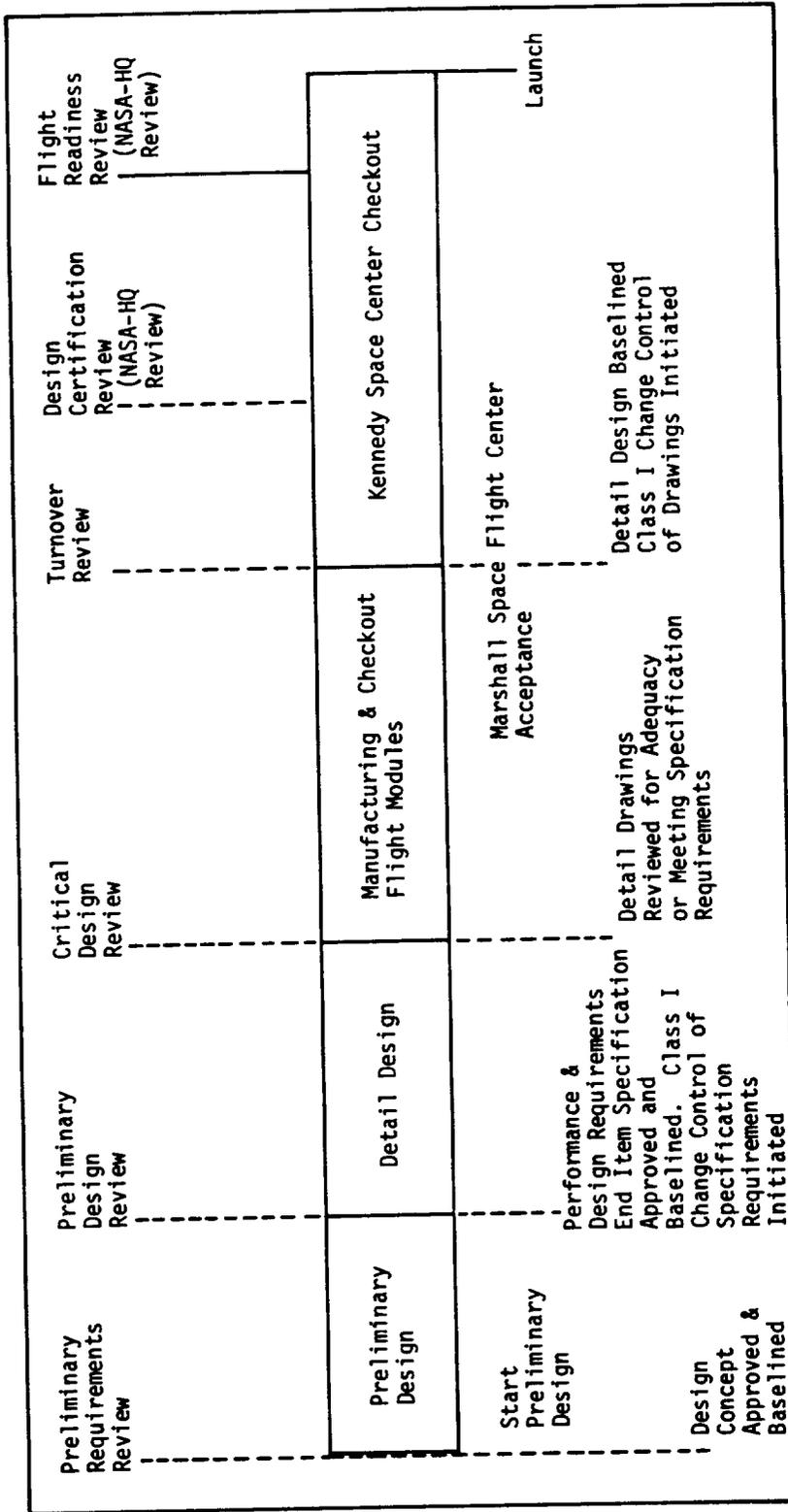


Figure II.B-1 Development Flow

Level	Approval Authority	Baselines or Approves Changes To--
Level I CCB	Apollo Applications Program Director	Program Level Requirements
Level II CCB	Center Program Managers	System Level Requirements
Level III CCB	Project Managers	End Item Level Requirements
Level IV CCB	Resident Managers	Approves Classification of Class II Changes
Level V CCB	Contractor or Marshall Space Flight Center Science & Engineering Branch	Approves Class II Changes

Figure II.B-2 Configuration Control Board Levels

the contractor to effect the change. Engineering changes that resulted in substantial cost savings, without compromising safety, performance, or schedules, received a high order of consideration by the CCB during the manufacturing activities preceding Turnover Review. Subsequent changes were minimized and approved only as necessary to correct safety hazards, improve reliability, or to comply with established performance requirements.

2. Documentation. Early in the development of the Configuration Management (CM) system, specific guidelines were unavailable for the Skylab Program. As a result, Saturn/Apollo Program Documents were used as models for complementing the Change Integration and Configuration Control Task. Later, CM requirements were imposed on the MSFC by NASA Headquarters with the issuance of the following guideline documents:

- M-D ML 3200-084 Skylab Program Directive No. 11A, entitled "Sequence and Flow of Hardware Development and Key Inspection Points", dated October 14, 1970.
- Operating Instruction ML-AA1-8040.1A, entitled "Level I Configuration Control Board", dated June 11, 1970.
- NASA Headquarters Bulletin NHB 8040.1A, entitled "Configuration Management Requirements", dated June 1971.
- M-D ML 3200.137 Skylab Program Directive No. 34, entitled "Skylab Program CCB Controls and Reporting Requirements", dated January 19, 1971.
- M-D ML 3200.149 Skylab Program Directive No. 58, entitled "Post Acceptance Change Control", dated July 6, 1972.

The initial Skylab documentation used was an MSFC planning document, AAP, Program Directive Number MPD 8040.11 entitled "AAP Systems Integration and Configuration Management Manual", MM 8040.10 dated August 1, 1969. This manual was revised to incorporate specific Skylab requirements because of the complexity of this multimodule program. The new manual, MM 8040.10A, entitled "Saturn/AAP/Engines Configuration Management Manual (MSFC)", dated February 17, 1970, was thereafter used as the guideline document. Based on this manual, Configuration Management Standard CM-027-001-2H was prepared with the intent of contractually imposing this document on all Skylab contractors, but actually was imposed on only the MDA Module CM effort. Each module contractor did, however, submit his own CM plans.

As the program developed, additional documents were developed and used for specific areas of CM disciplines, as discussed below:

a. Cluster Requirements Specification (CRS), RS003M00003. The CRS was written and maintained by the Integration Contractor as directed by MSFC. The AAP Program Specification SE-140-001-1 was used

as the basis for development of the CRS. Both specifications were baselined and placed under Configuration Control during 1969. The CRS defined performance and design integration requirements for the Skylab program. As differences between the Program Specification and the CRS were identified, action was initiated to resolve these differences either by changing the CRS or by proposing changes to the Program Specification, thereby maintaining compatibility between the two specifications throughout the life of the Skylab program. A total of 68 CRS Change Packages were initiated to either supplement or change requirements. Additionally, in February 1970, an MSFC memo was prepared to allow deviations to the CRS document. All such deviations became part of the CRS as Appendix K.

b. Skylab Program Stowage List 1-SL-002. The Stowage List was developed and initiated as an MSFC/JSC Inter-Center Document and was placed on contract in August 1970. This document presented the following information:

- (1) Weight data status and comparisons by identifying both specification weights and estimated or actual weights;
- (2) Quantities to be launched and their stowage locations by module;
- (3) Inflight transfer quantities and stowage locations by module;
- (4) Deactivation stowage locations and quantities by module, as well as command module return stowage configuration;
- (5) Cumulative quantity totals by module for all stowed items during launch, active orbit, inactive orbit, and return.

The stowage list was prepared in computerized format and updated monthly. Each revision contained an updated stowage list change log that identified all approved and disapproved changes since the previous revision.

Changes to the list were submitted by either an MSFC Engineering Change Request (ECR), Contractor Engineering Change Request (ECP), or a JSC Engineering Design Change Request (EDCR) with an attached Stowage List Change Notice (SLCN). This SLCN defined both the existing criteria and the proposed change criteria. All changes to the list were processed through the integration contractor's Change Integration Group by Level II CCB action.

c. Interface Control Document (ICD) Identification Matrix, 10M01840. This computerized matrix listed all ICDs for which MSFC was responsible and those which had an interface with other NASA Centers. For further details refer to paragraph II.B.4.a, Skylab ICD Matrix, herein.

d. Test Checkout Requirements and Specifications Documents (TCRSDs). The following TCRSDs defined the test requirements, disciplines and constraints for Skylab modules and hardware:

- (1) Integrated Systems, TM-012-003-2H
- (2) Orbital Workshop (OWS), 1B83429
- (3) Apollo Telescope Mount (ATM), 50M02425
- (4) Airlock Module/Multiple Docking Adapter (AM/MDA),

MDC E0122.

A Skylab procedure entitled "Test and Checkout Requirements and Specification Document (TCRSD) Test Change Notice (TCN)", SL-EI 593-72 was written and issued on October 10, 1972. An MSFC TCN form was designed for use in accomplishing all changes to the TCRSDs. A special Configuration CCB was established with membership from MSFC, KSC, and JSC. This Board functioned under Level II CCB authority and was operated by MSFC at KSC. Refer to paragraph II.B.3.e for additional details of the MSFC CM effort conducted at KSC.

e. Configuration Identification Index and Modification Status Reports. These reports were used to identify the approved (as-designed) configuration of Skylab by entering all new and updated hardware changes and those document changes that had a direct affect on the hardware. The computerized reports, prepared, published, and maintained by the Integration Contractors' Change Integration Group for the MSFC Project Offices, are identified as follows:

- (1) OWS, CM-020-001-2H
- (2) Experiment Development and Payload Evaluation,
CM-020-005-2H
- (3) MDA, CM-020-003-2H
- (4) ATM, CM-020-004-2H
- (5) AM, CM-020-002-2H

An additional report, the Electrical Support Equipment (ESE) document, was published and maintained as a separate report for the SL-GS Project Office.

f. Configuration Management and Engineering Integration Planning Documents. From August 9, 1970 through May 1972, the Change Integration Group was placed on special assignment to assist the MSFC Program Management Office (Engineering and Integration Branch) in preparation of Intercenter Agreements and Subagreements related to the Configuration Management of MSFC-furnished equipment. This effort also

included documenting various MSFC policies and plans to implement the criteria and requirements resulting from these agreements. Specific items documented include MSFC Program Directives 8040.14A and 8040.16, titled "MSFC Skylab Program Acceptance Data Package (ADP)" dated July 10, 1972, and "MSFC Skylab Program Pre-Delivery Turnover Reviews (PDTR)" dated May 24, 1972, respectively. Other documents were "MSFC/KSC Configuration Management Subagreements" (Marshall Management Instruction MMI 1058.1), MSFC Design Certification Review (DCR) Procedure, Procedure for Skylab Certificate of Flight Worthiness, and JSC/MSFC/KSC Inter-Center Agreement on Skylab Program Flight Crew Equipment Handling at KSC.

g. Open/Deferred Work Accountability Procedure. A procedure entitled "Use and Maintenance of the Skylab Open/Deferred Work Accountability System" (unnumbered) was written in April 1972, and final issue made on June 6, 1972.

This procedure described the use and maintenance of the special Skylab Open/Deferred work status capability established in the Configuration Management Accounting (CMA) system.

All open and deferred work affecting the Skylab Cluster hardware was tracked using a modified version of the existing CMA system. Open work was defined as those items that would be subject to tracking, including:

- (1) Nonconformances resulting from Customer Acceptance Readiness Reviews (CARR);
- (2) PDTRs;
- (3) Systems test and checkout activities;
- (4) Retrofit Modifications (MOD Kits) and tests that had been assigned to a new work location;
- (5) Work resulting from Field Engineering Changes (FECs).

Deferred work was defined as items subject to tracking, including the planned activities (work originally planned and scheduled for a specific location) such as, installation of experiments and solar array panels, scheduled tests at KSC, etc.

h. MSFC Crew Procedures Management Plan, Dated December 1972. This plan was developed in conjunction with the JSC Skylab Crew Procedures Management Plan, JSC-06842. The plan provided detailed guidelines to all MSFC personnel involved in the Crew Procedures change review activity. Details of this configuration function are delineated in paragraph II.B.3.f herein.

3. Integration and Control Activity

a. Change Review Board. The operation of the MSFC CRB was the responsibility of the Skylab Engineering and Integration Project Office. Its primary functions were to:

- (1) Review new change requests before entry into the system;
- (2) Review interface changes and assign the change to the appropriate CCB;
- (3) Review all requests for Level II action and schedule dispositioning action;
- (4) Review Level II Configuration Control Board Directives (CCBDs) before presentation to Level II CCB chairman;
- (5) Act as focal point for all types of problem changes (unresolved old changes currently in the system).

Upon receipt of a proposed change (contractor ECP, ECR, or EDGR), the assigned responsible engineer presented the change to the CRB and informed the board of its impact on hardware, schedules, program documentation, and its affect on other NASA Centers and contractors. After the board reviewed the change, it was either accepted into the Standard Change Integration and Tracking (SCIT) system or disapproved. Upon acceptance of a change, the CRB would assign responsibility to the appropriate Change Board for further action.

Whenever Level III boards required Level II disposition of a change, referrals were made to the CRB by a "Request for Level II Action." At this time, the responsible engineer would present the change to the CRB for Level II action and disposition scheduling. Upon completion, all Level II CCBDs were presented to the CRB for review. The CRB would review the CCBD, as presented by the responsible engineer, for completeness, accuracy, identification of all affected contractors, cost and schedule impacts, and identification of MOD/Kits, if required. After assurance of compliance with these criteria, the CCBD was routed to the appropriate Project Office for concurrence signature and ultimately to the Level II CCB chairman for final approval.

The CRB also functioned as the focal point for any changes which could not be dispositioned due to conflicts between contractors, interface engineers, etc.

b. Level II CCB. The Level II CCB was established within the MSFC Center by authority of the Skylab Program Director. The Level II CCB conducted regularly scheduled meetings and was chaired by the MSFC Program Manager, or a designated representative with decision-making authority for the actions of the Board.

All changes initiated by MSFC, MSFC contractors, or other NASA Centers, were submitted for Level II CCB approval, coordination (changes affecting other Centers) or referral to the Level I CCB for changes affecting Level I specifications or criteria. Engineering changes within the criteria of the MSFC Level II CCB activity consisted of

- (1) The CRS and Mission Requirements Document;
- (2) Saturn 1B or V launch vehicle interfaces;
- (3) Level A ICDs (Center to Center);
- (4) ICDs affecting three or more Project CCBs;
- (5) The responsibilities of three or more Project Offices;
- (6) Unresolved Project-Level CCB actions;
- (7) EDCRs and Change Requests (CRs) received from other Centers;
- (8) Project funding authorizations;
- (9) Operational activities that are the responsibility of other Centers;
- (10) Controlled milestones listed in Skylab Program directives;
- (11) Experiment Requirements Documents (ERDs) and Experiment Integration Requirements Documents (EIRDs);
- (12) The Stowage List, I-SL-002;
- (13) The TCRSDs for all modules;
- (14) Flight control and redline measurements;
- (15) Power Allocation Documents affecting flight modules and JSC-developed hardware.

c. Level III CCB. The Level CCB was a function of each Skylab Project Office. Its primary responsibilities were:

- Preparation of Level III CCBs to provide direction to applicable contractor;
- Review and disposition of changes covered by the following criteria.

(1) End item specifications and experiment design and performance specifications;

(2) Instrumentation Program and Components List (IP&CL) for flight modules (Flight control measurements were controlled at Level II by an ICD.);

(3) Changes affecting only one project office (AM, MDA, OWS, ATM, PS, Ground Support Equipment (GSE) and Experiments);

(4) TCRSDs for each flight module;

(5) Changes to the applicable Power Allocation Documents affecting each flight module.

d. Change Integration Group CCB Support Activities. Whenever a change was received by the Change Integration Group that was covered by either Level II or Level III criteria, it was scheduled for initial presentation at the next weekly CCB meeting. The responsible engineer prepared a PCN change package that contained the change paper plus any supporting data received up to that point. After the initial presentation of a change to the Board, the responsible engineer, in conjunction with the project system engineer, wrote the disposition of the change. A CCBD was prepared reflecting the appropriate disposition (approved as written, approved with changes, or disapproved). This CCBD was then resubmitted for final sign-off. Based on the CCBD disposition, a Change Order or Supplemental Agreement was prepared for transmittal to the applicable contractor.

e. MSFC Integration and Control Activity at KSC. MSFC Engineering and Contractor Change Integration personnel, transferred to KSC in September 1972, were responsible for establishing and operating the Level II CCB and the TCN Board Secretariats, and all related configuration management function, after hardware delivery to KSC.

(1) Level II CCB Activity. All CCBDs prepared at KSC were prefixed with a 700 series number (Example 700-72-0001) with the term "Skylab Resident Office at KSC" identified in the CCB block of the directives.

Ground rules to define the basic operation of the Level II CCB at KSC were issued by MSFC, describing the responsibilities of the Skylab Project Office on-site personnel and the interface between the CCB and the KSC Spacecraft Implementation Board (SCIB).

Following the release of the ground rules, meetings were held with the MSFC on-site Project Office representatives to review the responsibilities of each, relative to the change processing system. The on-site MSFC representative had the primary responsibility for obtaining KSC impact and coordination of a change. Expedited change activities were supported by the CCB operation at MSFC.

To assure continuing management visibility of hardware changes in process at KSC, weekly statistics on hardware changes and TCNs processed at KSC were maintained and provided to MSFC and the Contractor Change Integration Group. (Refer to Figure II.B-3 for example.)

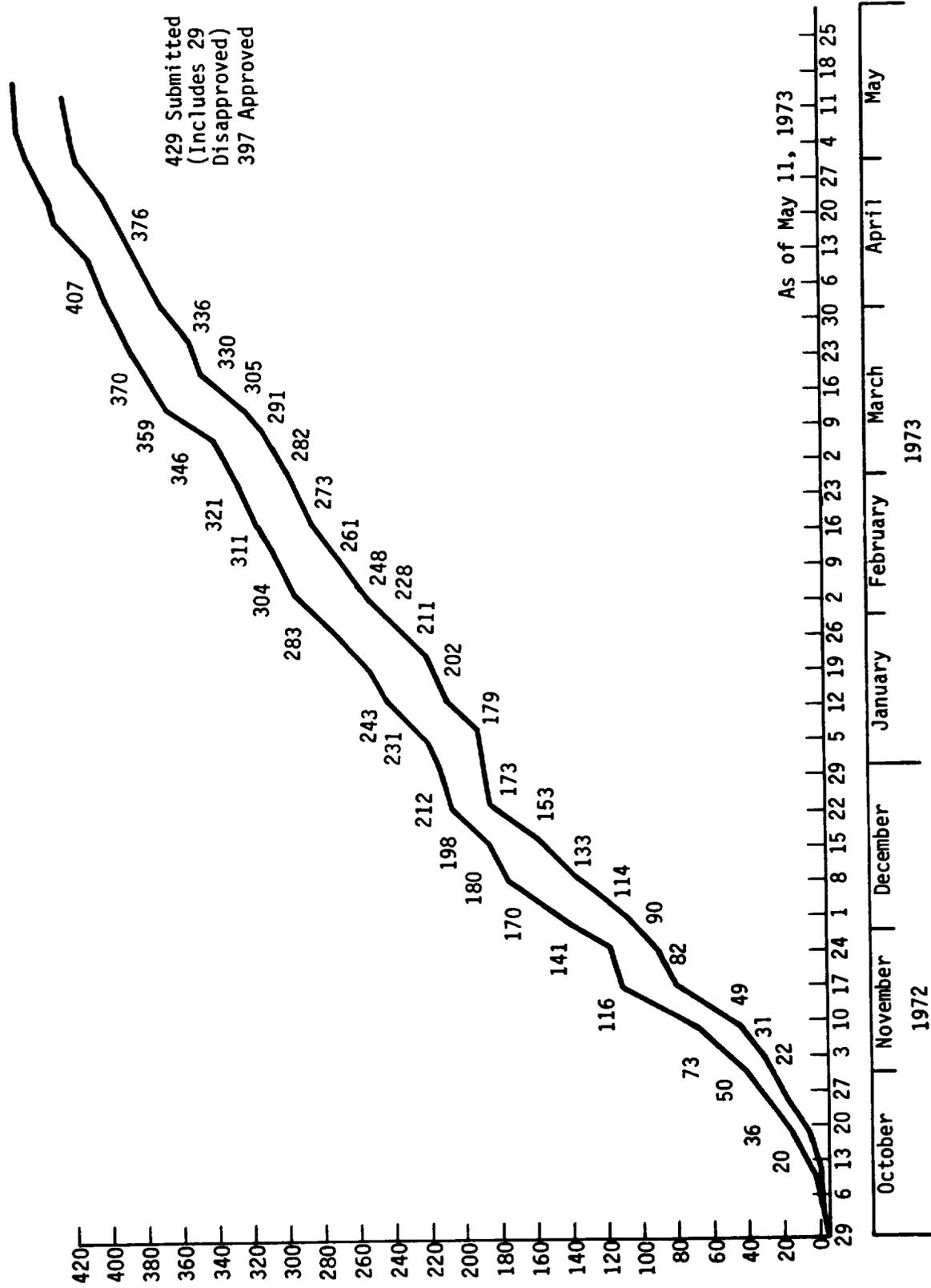
f. Crew Procedures Change Request Activity. At the request of JSC, an on-site MSFC Crew Procedures Resident Office was established at JSC in October 1972. This office was responsible for coordinating JSC/MSFC crew interface activities, and providing formal MSFC representation on the JSC Crew Procedures Change Control Board (CPCB). Contractor Change Integration personnel supported this activity at both Centers.

Actual flight crew procedures were released as "Basic" issues. These served as initial review copies to be changed and revised, as required. The next issue in the evolution of crew procedures was "Reference" copies, released approximately six months before the launch of SL-1. This was the first issue to come under direct strict change control. Based on approved changes to the reference issues, final crew procedures were published. Final issues were also subject to strict change control and, before final crew review and shipment to KSC, were changed by printed revisions and/or replacement pages. After final printing, crew comments and other last minute changes were incorporated by "pen and ink" changes written into the checklists.

Real-time change requests were initiated during the mission and were documented on JSC form 482D. Real-time changes to the onboard crew checklists occurred during the manned missions and were usually necessitated by mission anomalies or opportunities to improve science or systems performance. Because of their critical nature, real-time crew procedures change requests were processed somewhat differently than premission change requests. During the mission these changes were automatically forwarded to the HOSC. Upon receipt of a change, the Change Integration Engineer immediately coordinated it with each MSFC MSG and submitted MSFC comments to JSC via the MSFC Resident Office. Every effort was made to complete the review and coordination before the Flight Director's approval for uplink to the crew. In many cases, the MSFC review was conducted in two hours or less to support mission requirements.

Tracking and accounting at MSFC were accomplished using a modified version of the SCIT system. With the use of this computerized system, simultaneous coordination of many change requests and other documents having unique review requirements and schedules was possible. The modified SCIT provided timely listings of change requests received, reports of delinquencies, open items reports, and other documents (such as cross references), which made it possible to conduct and manage the coordination process in a timely fashion and with minimum personnel.

Each document (normally a change request) placed in the formal review cycle at MSFC was assigned a unique PCN. This number was assigned to the document initially and to all related documentation that followed. By use of the computer, this number along with unique



codes used to identify specific crew procedures, review organizations, document types, etc., permitted retrieval of cross reference listings and various special reports that provided statistical information for management reporting.

Figure II.B-4 shows the total number of change requests initially projected and those that were actually handled at MSFC. This includes requests distributed for information only, those requiring no MSFC action, and those requiring formal review.

4. Change Activity Tracking and Accounting. Major elements of the Change Integration and Configuration Control System used at MSFC for the Skylab Program consisted of:

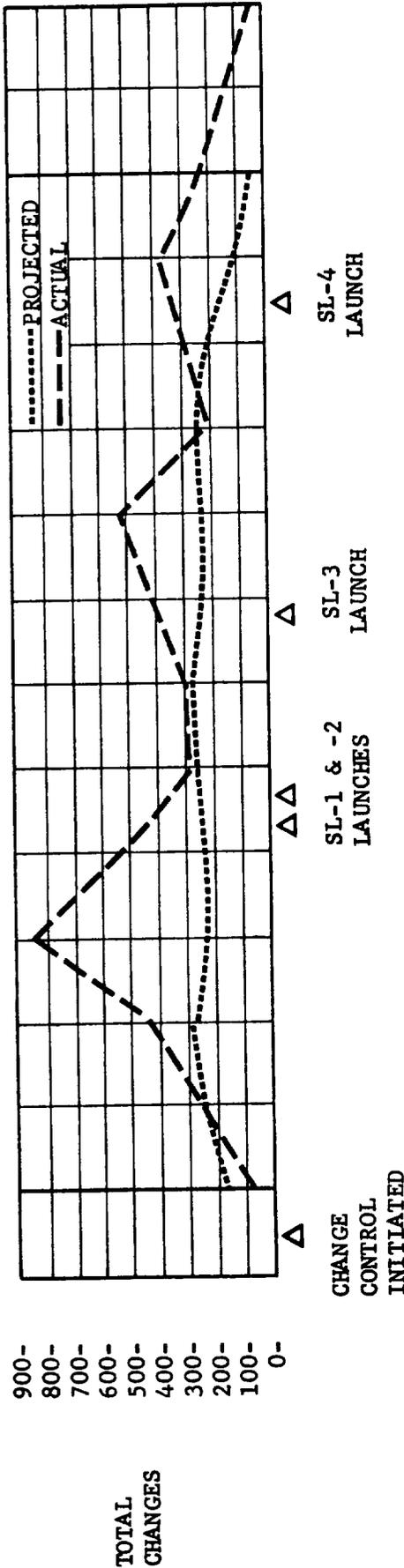
- Control of program requirements, such as plans, specifications, ICDs, CEIs, and End Items;
- Identification of changes such as MSFC ECRs, JSC EDCRs, KSC Change Requests, and Contractor's ECPs'
- Centralized Program Control with the assignment of PCN numbers and the scheduling of all actions required to disposition a proposed change;
- Technical assessment to determine the need for the change, the adequacy of proposed solutions and program impacts;
- Document decision and direct implementation of a change by CCBD, Change Order, or Contract Modification;
- Contractor's response by ECP or Record ECP;
- Verification of Change incorporation by means of CDRs, PDTRs, and Installation Notice Cards;
- Change Tracking and Configuration Accounting with the use of the MSFC computerized SCIT and CMA systems.

Tracking and accounting for the above elements provided Skylab Program Management with single change package control and total program impact, as well as visibility of all change elements being processed regardless of their complexity or the agencies involved. The system afforded daily identification to cognizant personnel to those actions needed and the person or group responsible for initiating positive actions. It also provided statistical data for gaging the program and design-to-cost status.

The Change Integration and Configuration Management Tracking and Accounting System consisted of the following functions:

1972		1973												1974	
D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	
150	250	275	240	210	250	300	250	230	260	200	100	50	*	*	
65	263	427	829	519	269	313	432	508	227	291	375	222	152	31	
64	246	314	803	505	264	312	419	505	213	288	366	222	138	30	
1	17	110	26	14	5	1	13	3	14	3	9	0	14	1	
0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	
3	104	224	164	54	64	104	129	169	134	62	89	109	78	5	
48	55	94	578	429	169	207	293	339	93	229	230	113	74	26	
14	104	109	87	36	18	2	10	0	0	0	56	0	0	0	
0	0	0	0	0	18	83	31	234	73	0	101	222	162	26	

PROJECTED
 TOTAL CHANGES
ACTUAL
 TOTAL CHANGES
 JSC INITIATED
 MSFC INITIATED
 KSC INITIATED
 MSFC REVIEW REQD
 DISTR FOR INFO ONLY
 NO MSFC ACTION RQD
 REAL-TIME CHANGES



* = No Original Projection Due to Planned Splashdown in December

Figure II.B-4 Summary of MSFC Crew Procedure Activities

- The SCIT System provided current status as well as a "cradle-to-grave" history of each change from its initial inception through contractual direction given to implement the proposed change.
- The CMA System established the requirements baselines and tracked authorized changes from the time of their formal approval through incorporation.

The SCIT system tracked the MSFC change flow, interface changes affecting other Centers, and the means of identifying hardware and software configuration requirements by CMA Tracking. These systems provided flexibility since most any combination of data fields could be selected, sorted, and reported in any desired order. The special usages developed for Skylab follow.

- Maintained current status and closeout action of all RIDs identified during program reviews;
- Defined ATM in-house as-designed/as-built configuration;
- Open work system, tracked and reported all open/deferred work to be passed on to KSC at turnover;
- Crew procedures, maintained accountability of MSFC technical coordination on crew procedure changes;
- Stowage, maintained accountability of all SLCNs;
- ICD, tracked ICDs through preparation coordination baseline and contractual acceptance.

a. Skylab ICD Matrix. The Skylab ICD matrix was a computerized listing of all ICDs for which MSFC was either responsible or had an interface with other NASA Centers. The matrix identified ICDs by number and title, and provided schedule status information. The matrix also identified the contractor responsible for generating the ICD, the level of the ICD, and the NASA engineer who was cognizant of the particular interface. All ICDs were identified and tracked until the document was baselined by MSFC CCBD action.

The computer program provided reports identifying:

- Total list of MSFC ICDs;
- List of all ICDs generated by an individual contractor;
- List of all ICDs for which an individual NASA engineer had responsibility;
- Listing of all MSFC ICDs in chronological order by contractor submittal date, by MSFC CCB submittal date, and by MSFC CCBD date.

This system was updated daily to reflect the latest action against each ICD. On a monthly basis, the ICD Identification Matrix, 10M01840, was published and distributed to all affected contractors, MSFC Engineering Laboratories and responsible NASA engineers.

b. Open Work Accountability. The open work accountability system was a specialized application of the CMA System that permitted storage and retrieval of work items by:

- Module/Project Office;
- End Item/Serial Number;
- Source,
- Responsibility,
- Type,
- Location,
- Schedule.

A change was entered into the system at the point of Acceptance/DD250 and tracked through launch.

5. Conclusions and Recommendations. The overall Configuration Management effort conducted on the Skylab Program enhanced the integrity of all program elements.

By establishing a total Configuration Management System, with direct responsibility for its functions assigned to a Change Integration Group, the MSFC Engineering and Integration Branch afforded total program visibility to all active participants.

With the establishment and implementation of the Configuration Management System, resultant advantages were derived, such as (1) total management visibility and statusing for change integration and configuration accountability; (2) tracking of change actions between NASA Centers and their contractors; (3) multimodule hardware configuration accountability for each flight; and (4) the statusing and accountability of all hardware, software, and documentation change activity throughout the fabrication, installation, and checkout phases.

In conclusion, it can be stated that in any multimodule effort where complex interfaces are encountered, and a variety of sources are used in supplying equipment, hardware, and documentation, an organized configuration management system developed and implemented early will enhance the integrity of the program.

During the scope of the Skylab CM effort, certain lessons were learned based on problems and their ultimate resolutions. These are briefly stated below and are offered in this report as recommendations to be considered in any future endeavors.

a. Uniformity of CM Requirements. Imposing CM requirements on all contractors early in the program will help reduce duplication of effort, unnecessary costs, and incompatibilities between contractors' systems. Change Integration and Configuration Control disciplines should be established before the first major module PDR.

b. Change Integration Group. Establish this group to engage in change control before and during baselining of the hardware and related documentation.

c. Program Control Numbering System. Many advantages are derived from the single-change-package concept, especially in a multimodule program.

d. Change Integration Engineers. This cradle-to-grave approach works to the advantage of a program in that one individual is totally responsible for, and knowledgeable of, the total change package.

e. Change Review Board. It would be helpful to assign signature authority to the CRB Chairman for all documentation changes to expedite same. This board should also be responsible for review of change package closures to negate the need for package review and closure at program's end. This will reduce manpower needs and related costs.

f. Configuration Control Boards. Establish requirements for each Board, regardless of level, to convene on a weekly basis. Working changes outside a board meeting cause delays in dispositioning and issuing direction to contractors. It would be beneficial to issue uniform direction to suppliers, especially when interfaces are involved. CCBD forms used by the various NASA Centers are distinctively different; a standard form would aid recipient contractors in complying with given direction regardless of the NASA source. The MSFC Directive form and procedures for the completion is recommended.

g. Standard Change Integration and Tracking System. Provides required visibility through reports and change listings making it possible to conduct and manage a complex coordination process in a timely manner with minimum personnel.

h. Interface Control Documents. Preparation of an Interface Management Requirements Document and imposing it on all program participants is a necessity.

i. Cluster Requirements Specification. Generate early in program and impose as contractual direction on all major hardware contractors for use as a guideline document in preparing Contract End Item Specifications.

j. Control of Documentation. Baseline program documents early and place under Configuration Control authority thereby providing a more acceptable hardware control with visibility as to which documents require change because of a hardware change.

k. Open/Deferred Work. Establishing and imposing open/deferred work requirements and an accountability system for this work is a prerequisite to any multimodule program. Early establishment precludes problems arising at the time of hardware turnover to the government and provides the required program management visibility subsequent to turnover.

l. Inter-Center Subagreements. Early development and use of agreements between NASA Centers is highly desirable and will prevent misinterpretation of requirements and obligations.

m. Change Tracking and Accounting. The SCIT System provided visibility to Engineers, Contractors, Project Offices, and NASA Management with current listings of changes received, open item, and delinquency reports. This made it possible to conduct and manage a complex coordination process in a timely fashion with minimum personnel.

C. Mission Planning and Analysis

Special studies were conducted to determine the impact of requirements or changes on systems, experiments, and crew activity time lines. To quote one example: The electrical power used was generated by solar arrays that had to face the sun most of the time. In approximately 4000 revolutions around Earth, this sun-oriented attitude did not provide an attitude suitable for Earth viewing by built-in instruments. Consequently, for Earth Resources Survey investigations, the vehicle's attitude had to be changed to allow the sensors to point directly at Earth and to maintain this Earth pointing attitude throughout the data taking pass. To further complicate the problem, except during high Beta Angle periods, Skylab passed from sunlight to darkness every revolution around the Earth. This required that energy needs during each dark period be provided by batteries that had to be charged during the sunlight passes. Another consideration in planning Skylab operations to support Earth Survey Experiments was the Attitude Control System and its requirements and limitations.

Changes in vehicle attitudes were implemented in two ways: the prime method was applying disturbing torques to combinations of three massive gyroscopes (Control Moment Gyros) so that reactive deflections in the desired direction and magnitude could be achieved. The secondary system was propulsive in which gas was expelled from nozzles to produce rotation in the required direction. Both systems had limitations primarily in the rates of attitude change that could be achieved economically; initiation of too great a rate would saturate the momentum storage capabilities of the gyros requiring expenditure of thruster gases for desaturation, and too frequent use of the thrusters would result in depletion of the stored gases.

Operational techniques were developed that would provide enough earth survey pointing opportunities while conserving electrical power and attitude control margins, and these techniques were modified during the third mission when one of the control moment gyros failed.

1. Mission Definition

a. Orbit Definition. During the period of Skylab orbit planning and definition, the baselined orbital parameters were going through many alterations. There were many considerations in the choice of final orbit definition. The Orbital Assembly (OA) altitude had to be high enough to allow sufficient orbital lifetime to complete the defined mission, and to minimize the effects of atmospheric shadowing on solar observing experiments. It had to be low enough to meet the payload capabilities of the SWS launch vehicle, allow reasonable propellant reserves and rendezvous durations for subsequent flights, and minimize radiation exposure on the crew and equipment from the high altitude radiation belts. The orbital inclination had to be sufficient to accomplish the desired coverage of the earth's surface for the Earth

Resources Experiments Package (EREP), and still remain within the payload capability of the launch vehicle. The history of these OA orbital parameters is as follows:

<u>APPROXIMATE DATE</u>	<u>ALTITUDE</u>	<u>INCLINATION</u>
Apr 1968	230 n mi Circular	28.9 deg
May 1968	220 n mi Circular	28.9 deg
Oct 1968	185 x 210 n mi	35 deg
Dec 1968	185 x 193 n mi	35 deg
Jan 1969	185 n mi Circular	36 deg
Aug 1969	235 n mi Circular	35 deg
Jan 1970	235 n mi Circular	50 deg
Aug 1972	233.8 n mi Circular	50 deg

After the orbit definition stabilized in approximately January of 1970, the only additional modification was made in August of 1972. This modification lowered the orbit from 235 to 233.8 n mi so that Skylab would traverse the same ground track every 71 revolutions. This altitude was to be maintained throughout the mission by periodic CSM Reaction Control System (RCS) burns or "trims". This facilitated EREP planning, training, operations, and data return, and facilitated prediction of trajectory related events.

b. Unmanned Activation Sequence. With the evolution of the program, the requirements for the initial activation of the workshop were definitized. The following is a summary of the unmanned activation sequence:

<u>DATE</u>	<u>ITEM</u>
July 1969	TB4 - Insertion
	TB4+0.4 Sec - Separation from S-II stage
	TB4+15 Sec - Maneuver to retrograde local horizontal; MDA pointed in direction opposite of velocity vector X^0 out of orbital plane.
	TB4+13 Min - Jettison payload shroud
	TB4+14 Min - Maneuver to solar inertial (XIOP)
	TB4+24 Min - Deploy OWS array
	TB4+46 Min - Deploy ATM
	TB4+61 Min - Deploy ATM array
	TB4+85 Min - Energize ATM control system
	TB4+85 Min - Begin CMG spinup
	TB4+7.3 hrs - Transfer control to CMG
February 1970	To - Liftoff
	To+1 hr - MDA/AM and OWS pressure check
	To+4 1/2 hr - Vent MDA/AM to 1.3 psia N ₂
	Vent OWS LH ₂ tank to 1.3 psia N ₂ Vent OWS LOX tank to vacuum

<u>DATE</u>	<u>ITEM</u>
February 1970	To+ 5 hr - Pressurize MDA/AM with O ₂ to 5.0 psia O ₂ /N ₂
	To+ 5 1/2 hr - MDA/AM Pressure integrity check
	To+ 5 1/2 hr - Pressurize OWS LH ₂ tank with O ₂ to 5.0 psia O ₂ /N ₂
	To+ 7 1/2 hr - Safe IU oronite/water
	To+ 7 3/4 hr - Transfer TACS control from IU to ATM PCS; dump IU water
	to+13 1/2 hr - OWS LH ₂ tank pressure check
May 1970	TB4 - Insertion (To+9 Min)
	TB4+2 Sec - Issue S-II/S-IVB separation signal
	TB4+4.5 Sec - NPV (nonpropulsive vents); Pitch to retrograde through GG
	TB4+4.8 Sec - Jettison payload shroud
	TB4+6 Min - Deploy ATM; Deploy discone antennas
	TB4+12 Min - Deploy ATM arrays
	TB4+27 Min - Deploy OWS arrays
	TB4+31 Min - Deploy meteoroid shield; Acquire solar inertial attitude
	TB4+52.5 Min - Initiate CMG Spinup
June 1972	TB1 = SL-1 - Liftoff
	TB4 = S-II - OECO (TB1+578 Sec)
	TB4+10 Sec - Insertion Pitch to solar inertial
	TB4+20 Sec - Activate OWS refrigeration system
	TB4+30 Sec - Initiate NPV (OWS habitation area and waste tank)
	TB4+5.5 Min - Jettison payload shroud
	TB4+5.7 Min - Activate AM deploy buses
	TB4+6.25 Min - Deploy discone antennas
	TB4+6.5 Min - Deploy ATM
	TB4+15 Min - Deploy ATM solar arrays
	TB4+27 Min - Activate ATM telemetry
	TB4+32.4 Min - Deploy OWS solar arrays
	TB4+43.7 Min - Activate ATM thermal control system
	TB4+ TBD - Initiate CMG spinup
	TB4+86.2 Min - Deploy meteoroid shield
	TB4+1.5 Min - Deactivate AM deploy buses
	TB4+3 hr - Dump OWS pneumatics
	TB4+4.5 hr - Transfer TACS control from IU to APCS at about 25% CMG angular momentum
February 1973	TB1 = SL-1 - Liftoff
	TB4 = S-II - OECO (TB1+588.696 Sec)
	TB4+6 Sec - Initiate NPV (OWS habitation and waste tank)
	TB4+10 Sec - Orbital insertion; Pitch solar inertial (Jettison payload shroud when SWS passes through nadir)

<u>DATE</u>	<u>ITEM</u>
February 1973	TB4+20 Sec - Activate OWS refrigeration system
	TB4+5.7 Min - Activate AM deployment buses
	TB4+6.2 Min - Deploy discone antennas
	TB4+6.5 Min - Deploy ATM
	TB4+15 Min - Deploy ATM solar arrays
	TB4+27 Min - Activate ATM telemetry
	TB4+31.2 Min - Deploy OWS solar arrays
	TB4+86.2 Min - Deploy meteoroid shield
	TB4+87.2 Min - Activate APCS
	TB4+1.5 hr - Deactivate AM deploy buses
	TB4+3 hr - Dump OWS pneumatics
	TB4+3 hr 1.2 Min - Activate ATM thermal control system
	TB4+4 hr 40.2 Min - Transfer TACS control from IU to APCS at about 20% (1800 rpm) CMG angular momentum

2. Orbital Trajectory Analysis

a. Launch Sequence. Before the decision to fly the dry workshop, the launch sequence was defined as follows: first the launch of the SWS on a S-IB launch vehicle (AAP-2). Approximately one day later the first manned CSM (AAP-1) would be launched on a S-IB vehicle for a mission of up to 28 days. Subsequent to this first manned mission, a second CSM would be launched, also using a S-IB booster, in conjunction with a separate S-IB launch of an unmanned spacecraft lunar adapter, and a lunar module/apollo telescope mount spacecraft (AAP-3/4). These would dock with the SWS and perform a mission of up to 56 days duration.

After the decision to fly the dry workshop, a new launch sequence was constructed that was similar to the previous one except for modifications in named sequence and mission definition. The first launch was that of the SWS on a S-V launch vehicle (SL-1). Approximately one day later the first manned CSM launch (SL-2) would take place using a S-IB vehicle. This mission was to have a duration of up to 28 days. After the return of this crew, the next manned CSM would be launched (SL-3), again on a S-IB vehicle, for a mission duration of up to 56 days. The final manned CSM (SL-4) would be launched, once again on a S-IB, subsequent to the return of the SL-3 crew. This mission, as the previous one, was to have a duration of up to 56 days. The desired interval between launches of the manned CSMs was set at 90 ± 6 days. The 84 day minimum was the launch pad turnaround limit while the 96 day maximum was to constrain the total length of the mission requiring the workshop.

b. SWS Attitudes. The primary mission SWS attitude, as well as the attitude required for CSM docking, experienced considerable modification. Attitude planning as of March 1968 indicated that the SWS was to be maneuvered to a gravity gradient attitude during rendezvous

and docking of the first manned CSM. The primary attitude for the remainder of that mission was to be solar inertial (SI) with the X-axis of the SWS perpendicular to the orbit plane (X-POP). During the storage period between manned missions, the SWS was to be put into a gravity gradient attitude. The second manned mission was to use the same docking attitude and was to be performed with SWS primary attitude being SI with the X-axis in the orbit plane (X-IOP). Documentation dated October 1968 indicated that rendezvous and docking for all manned missions would be carried out with Skylab in X-POP with the MDA pointing northward. The rendezvous and docking attitude was later refined so that documentation dated May 1969 indicated an attitude of X-POP with the Z-axis along the local vertical (Z-LV). The remainder of the mission was to maintain the X-IOP primary attitude.

With the advent of the dry workshop concept, the primary mission attitude was redefined as SI, X-IOP and this was to be the baseline for all Skylab missions and storage periods. The intent at that time was to maintain this attitude for rendezvous and docking. Documentation dated March 1971 indicated that a decision had been made to change the SWS attitude for rendezvous and docking from the basic SI, X-IOP to the Z-LV attitude. In addition, the Z-LV attitude was indicated for use during the EREP passes.

The attitudes actually used in the Skylab missions were those indicated in documentation dated October 1971. The primary Skylab attitude would be SI with the X principal axis in the orbit plane, pointing along the velocity vector at orbital noon, with the +Z axis pointing toward the sun. The attitude for rendezvous, Z-LV(R), was to be Z local vertical with the X geometric axis in the orbit plane, and -X axis in the direction of the velocity vector and the -Z axis pointing toward the earth. If the beta angle was greater than 50 degrees, then the SWS would be biased about the X-axis to a maximum of 23.5 degrees from the basic Z-LV(R) attitude. The attitude to be used during the EREP passes, Z-LV(E), was similar to that used in the Z-LV(R) except that the +X axis pointed in the direction of the velocity vector.

c. Drag Decay and Orbital Lifetime. The drag acting on an orbiting spacecraft depends upon the altitude of that spacecraft and the level of solar energy striking the atmosphere. Lower altitudes cause the spacecraft to travel through more dense atmosphere thereby increasing drag. Higher levels of solar energy cause an increase in altitude of the atmosphere (expansion) and thereby has the same affect as a lower orbit. The amount of drag and the mass of the spacecraft directly determine the orbital lifetime. Increasing mass tends to lengthen the lifetime while increasing drag tends to shorten it.

SL-1 SWS insertion altitude of 235 n mi was finally chosen to provide a rendezvous compatible orbit and to assure that the OA would not decay below a minimum altitude of 210 n mi at the end of the eight-month mission. This resulted in a predicted nominal orbital lifetime of approximately 2050 days.

With the advent of trim burns for the repeatability of ground tracks, the altitude at the end of the eight-month mission was still near the insertion altitude of 234 n mi. Including these trim burns into the decay and lifetime analysis for the OA resulted in extending the orbital lifetime by approximately 700 days and consequently modified the uncontrolled decay history to start at the end of the eight-month mission. This resulted in a nominal predicted orbital lifetime of 2730 days from the launch of the SWS.

d. **Beta Angle Relationships.** The orientation of the orbital plane relative to the earth and sun had been used in the design of the Skylab thermal control systems, solar power systems, attitude control systems and a planned mission profile. This orientation of the orbital plane is given by the celestial angle beta, where beta is defined as the angle between the sun and orbital plane in a plane perpendicular to the orbit plane that includes the earth-sun line. In project documentation relative to mission requirements, trajectory planning and flight planning, beta has been considered positive when the sun is north of the orbit plane.

There were many systems and experiments on board Skylab that were constrained by the beta angle or the length of the orbital daylight and darkness, which is a function of the beta angle. Power availability to the SWS was directly dependent upon the duration of sunlight impinging on the solar arrays.

The scheduling of Z-LV(E) passes for EREP experiment performance had to consider the effects of beta angle on the SWS systems. Target lighting conditions, required for certain EREP experiments, were related to the beta angle. Several other experiments required a knowledge of the nighttime duration for optimum scheduling and operation.

The beta angle also had an influence on the procedure for the attitude change when entering the rendezvous Z-LV(R) attitude. If beta was greater than 50 degrees, the SWS had to be biased about the X axis so the CSM transponding antenna could view the OWS antenna.

A plot of the beta history is a sinusoidal curve whose amplitude is bounded by a sinusoidal envelope that follows the seasonal motion of the sun. The origin of the envelope depends on the date of launch while the origin of the internal curve depends on the time of launch. Consequently, the beta history for Skylab depended on the choice of final launch date and time.

During the flight of Skylab, the beta angle history was such that there were two periods during the manned portion of the mission during which Skylab was in constant sunlight. These occurred during the first and third manned missions.

3. Launch Vehicle Trajectory Analysis. Because the manned CSM missions were to rendezvous and dock with the SWS, the SWS trajectory

established the framework for the launch planning of subsequent manned missions. The altitude and inclination of the SWS had to be such that the CSMs were capable of rendezvous and docking. The time of launch of the SWS had to be such that the launch windows for the subsequent CSM launches occurred at times that satisfied the lighting and abort constraints.

To accomplish rendezvous, each CSM launch had to occur within specific launch windows during which the orbiting SWS was in the proper phase angle relationship with the launch site. These windows consisted of an optimum point at which time the launch and insertion would occur with minimum booster propellant use and a time margin during which launch could still take place but with increasing use of propellant for yaw steering. The duration of the launch window determine the maximum weight of booster propellant to be allocated for yaw steering and dictated a specific loss in the amount of payload that could be inserted in orbit.

Payload capability for a specific booster depends on the desired altitude, inclination, launch azimuth, and first decending node. Increasing the altitude requires a reduction in payload. Deviations from an optimum inclination of 28.9 degrees (due east launch from Cape Kennedy) require reductions in payload. The selection of launch azimuth and decending node affected the ultimate payload capability in that they defined the quantity of propellant required for yaw steering.

As the orbit for Skylab varied in the planning stages, so did the payload capability. During the wet the wet workshop period, the payload capabilities of the S-IB launch vehicles were as follows:

<u>APPROXIMATE DATE</u>	<u>MISSION</u>	<u>PAYLOAD CAPABILITY</u>
July 1968	AAP-1	39,200 lb
	AAP-2 (SWS)	31,100 lb
	AAP-3	39,800 lb
Based on a SWS altitude of 220 n mi inclination of 29 degrees		
October 1968	AAP-1	38,017 lb
	Based on a CSM altitude of 185 x 210 n mi inclination of 29 degrees	
January 1969	AAP-1	38,780 lb
	AAP-3A	39,350 lb
	Based on a CSM altitude of 81 x 120 n mi inclination of 35 degrees	

During this period, it was planned to have a southerly launch azimuth for the manned missions to minimize the land mass being overflown. These azimuths were 112 degrees in October 1968 and 110 degrees in January 1969. The SWS was to be launched on a northerly azimuth of 65 degrees as indicated in documentation dated January 1968. The decending node at this time was indicated as 50 degrees and 134 degrees for the CSM and the SWS launch, respectively.

After the dry workshop concept was baselined and the planned inclination was changed to 50 degrees, the payload capability of the boosters went through further modification. Documentation dated July 18, 1969 indicated that the payload capability of the Saturn V booster was 198,000 lb for an orbit of 260 n mi circular and 50 degrees inclination. For the same inclination and an altitude of 81 x 120 n mi, the S-IB had a capability of 37,200 lb. With the advent of the 50 degree inclination, it was decided that northerly launch azimuths should be baselined for the CSM launches. Because of the increased inclination, it became desirable to incorporate a variable azimuth capability in the manned launch vehicles. Before this time a single launch azimuth was set for the entire window duration. For a 50 degree inclination this could have been costly unless the launch took place at the instant for which the preset azimuth applied. A variable azimuth could be reset for the specific time of the launch and thereby would conserve propellant and have additional payload capability or, optionally, increase the size of the launch window. This option was available as the launch window was defined during the time period as the time duration during which less than 700 pounds of propellant would be used to accomplish all necessary yaw steering.

The following is a history of the payload capability after the decision to fly the dry workshop. All manned launch payload capabilities are exclusive of 700 pounds of yaw steering-allocated propellant and 2000 pounds of flight performance reserves propellant. The insertion altitudes for the SWS and CSMs are 235 n mi and 81 x 120 n mi, respectively. The inclination is 50 degrees.

<u>APPROXIMATE DATE</u>	<u>MISSION</u>	<u>PAYLOAD CAPABILITY (Pounds)</u>
February 1970	SL-1 (SWS)	184,325
	SL-2	35,300
	SL-3	35,800
	SL-4	35,300
June 1971	SL-1 (SWS)	210,022
	SL-2	35,300
	SL-3	35,400
	SL-4	35,300
February 1972	SL-1 (SWS)	212,725
	SL-2	36,768
	SL-3	36,230
	SL-4	37,450

The final launch parameters for the planned mission were as follows:

<u>MISSION</u>	<u>TARGETED AZIMUTH (deg)</u>	<u>DESCENDING NODE (deg)</u>
SL-1	40.88	153.25
SL-2	47.035	155.021
SL-3	46.190	154.828
SL-4	45.382	154.601

4. Conclusions and Recommendations. In reviewing the Skylab mission design and the supporting studies and analyses performed, it is concluded that the methods used were as logical and valid as the state-of-the-art would allow. Each hardware development (component, system, or launch vehicle) change that impacted the mission parameters set off a new series of analyses and computer runs that resulted in changes to orbit attitude, inclination, launch date, or other requirement. It is recommended that future programs be developed by the same basic approach.

D. Special Engineering Analysis

1. Contingency Analysis. In the period preceding the launch of SL-1, a program was initiated to analyze the potential show stoppers in the Skylab program, with particular attention devoted to the SL-1 sequence. Some events in the SL-1 sequence were irreversible and, if a problem occurred, probably little could be done to remedy the situation. An example of this type of failure would be an inability to jettison the payload shroud. Most other events, however, were not considered catastrophic and an integrated effort was initiated by MSFC to study the most significant items. The philosophy associated with this effort was that, if a problem did not occur that was identical to the problem analyzed, the effort was still useful because the involved personnel "had been down the street before", i.e., they were familiar with the system and how it operated. They were, therefore, more capable of dealing with a problem occurring in real time.

a. Feasibility Study. Preliminary studies resulted in identification of the following events to be analyzed. Inability to:

- close MDA vent
- jettison radiator shield
- deploy ATM
- deploy ATM solar arrays
- deploy OWS solar arrays
- vent OWS habitation area
- deploy discone antennas
- release lock on ATM canister
- deploy meteoroid shield

Loss of:

- ATM thermal control
- AM telemetry
- one control moment gyro

b. Detailed Studies. For each contingency analyzed, a preliminary study was conducted. Detailed areas needing further study were supplied to each MSG. The MSGs, with appropriate contractor support, conducted detailed analyses pertaining to their particular discipline, i.e., electrical power (load models, thermal models, mechanical feasibility, crew simulation).

The significant question was "would there be sufficient electrical power and thermal control to conduct a mission, and if so, what is the mission?" Results of the analysis indicated that not only was there a feasible mission, but that it could be near-nominal as originally planned if:

- careful power management procedures were initiated, and
- the launch of the manned vehicles be scheduled to structure the high activity periods of the mission during periods of high beta angle.

The individual responses by the MSGs were then combined into an integrated resolution of the contingency. The analyses were continued in sufficient depth to determine adequate workarounds and to identify any special provisions necessary to accomplish the workaround.

The following problems were addressed just two weeks before the scheduled launch of SL-1. The problems were identified during a mission simulation conducted at JSC with support provided by MSFC and contractor personnel:

- Inability to deploy the ATM solar arrays
- Inability to deploy the OWS solar arrays
- Inability to deploy the meteoroid shield and the OWS solar arrays.

Coincidentally, the anomaly that occurred early during SL-1 flight paralleled the circumstances of this analysis in many ways and the analysis results were applied directly in development of alternate mission plans.

c. Conclusions and Recommendations. The experiences encountered in conducting the Skylab mission emphasizes the importance and the usefulness of conducting studies of this type. Of particular significance is the experience and the increased familiarity gained with the various systems operational modes by the individuals performing the analysis, and their ability to transfer that familiarity to the problem at hand.

During the Skylab mission, real-time studies were continued in the following areas because of the real-time problems:

- OWS solar array deployment
- Affect of loss of meteoroid shield on thermal balance
- Power system (battery) degradation
- AM coolant loop degradation
- Reserves study for the actual SL-1 configuration, i.e., electrical power available, electrical loads, thermal, and commodities reserves.
- Loss of cooling loop for ATM control panel and Earth Resources experiments.

It is recommended that analysis programs be initiated early so results may influence design of the systems and perhaps avoid some of the potential failure modes inherent in most systems. Also, the contingency analyses should be closely correlated with Failure Mode Effects Analysis and identification of "single failure points" and "critical items."

2. AUTOSCAN Performance Report. The Skylab program was designed to extend the duration of manned space flight and carry out a broad spectrum of experimental investigations, using pulse code modulation (PCM) telemetry systems developed during the Gemini and Apollo programs

to transmit approximately 1800 data measurements to the various ground stations. It was estimated that four billion bits of data could be transmitted during a 24 hour period. This is equivalent to approximately one million pages of computer printout per day with 500 data values per page.

The task of reviewing/analyzing this volume of data, required the development of two data handling methods - Data Compression and AUTOSCAN. Data compression removes all redundant data points in the fixed format of the telemetry system and affixes an identifier and time to each of the remaining data points. This was accomplished with a zero order predictor (ZOP) algorithm at the ground station that permitted transmissions from the station only when a change in the value of the downlinked measurement had occurred. AUTOSCAN is an acronym for a digital computer program designed to search the data for points that exceed some predetermined limit. The information is for use in performing daily systems analyses and to indicate areas that require further investigation.

a. AUTOSCAN Program. An AUTOSCAN Task Team was organized in December 1970, to develop and implement the AUTOSCAN concepts. The Task Team responsibilities are given in the "AUTOSCAN Implementation Plan," ED-2002-1392.

Reviews of various automated scanning programs were conducted, searching for techniques that might be incorporated in the AUTOSCAN program and problem areas to be avoided during development of the AUTOSCAN program.

Numerous meetings were held with MSG personnel to familiarize them with the AUTOSCAN concepts and to define the types of requirements needed to assist in program definition. To facilitate this, all the on-board measurements were grouped in system/subsystem categories. This allowed concentration on a smaller volume of measurements at any one time rather than treating the entire volume of measurements.

As each MSG Leader (MSGL) presented their respective scan requirements, they were reviewed and used to help define the basic program concepts. In this initial phase, sufficient requirements were submitted to establish the majority of measurement types that the program must accommodate. Actual scan limits for nondiscrete measurements were provided for only a minority of the measurements, but this was sufficient to define program requirements for scanning. The program concepts formulated were provided in prose and flow chart form to programmer/analysts for the programming and coding required to implement these concepts. The flow charts provided were detailed and complete, but were used only as guides by the programmer/analysts in developing the program.

The development and implementation of the AUTOSCAN program was an iterative process through six versions, with each subsequent version possessing some capability over the previous version. Separate programs were developed for the AM and ATM all Digital Data Tape (ADDT) to provide sufficient computer core storage for both AM and ATM telemetered

measurements. The ATM scan program was developed and checked out first and then the necessary additions, deletions, and modifications made to provide an AM scan program.

The special modules resulted from the review of the data users requirements, some of which could not be accomplished with the basic program concepts (event, limit, and statistical scans). Special computer subroutines (modules) were developed to handle the expanded requirements, which included cyclic, slope, and consumables data types. Examples of other types of special modules are:

- Limit scan activated by an analog measurement
- Limit scan activated by a discrete and analog measurement
- Limit scan activated by a discrete and two analogs
- Change of units of measurement in output
- Limit scan activated by two analogs
- Processing activated by limit violation of analogs plus a delta stop time.

Specifications and detailed flow charts for the special modules were submitted for programming as the special module requirements developed. Each special module was submitted as it became available, with all special module specifications and flow charts presented in the "AUTOSCAN Program Requirements," ED-2002-1400, Rev C document for formal release. The document was released in various revisions five times between November 1971 and June 1973 to incorporate new special modules or modify existing ones as needed.

Measurement scan requirements received from the data users were incorporated into the "AUTOSCAN Measurement Requirements," ED-2002-1387, Rev F document which served as a data base for AUTOSCAN and contained all the onboard measurements together with pertinent information to identify all limit and discrete scan requirements for individual measurements. This data base was used to prepare the preprocessor that contained the input requirements used by the AUTOSCAN program. The continuous influx of requirements was reflected by periodic releases of the Measurement Requirements Document. The document, in various revisions, was released seven times between November 1971 and February 1974.

The development of the AUTOSCAN Implementation Plan was initiated in mid-1971. The document was not a comprehensive description of the AUTOSCAN program but described the guidelines for implementing the AUTOSCAN system, and the program implementation activities, both before and during the mission. This document was released three times between December 1971 and September 1972.

Internally generated data were used to check out the earlier versions of the program. These prototype programs were useful in sizing the input and output, computer storage, and the amount of computer time required. These considerations lead to the elimination of most special modules except on an individual basis.

Checkout and improvement continued through 1972 using data primarily from various Skylab module tests, including JSC, and KSC testing. The outputs were reviewed and all problems identified to the programmer/analysts. Some problems were experienced during these reviews, e.g., anomalous appearing behavior for a measurement could not be ascribed to a particular source (i.e., AUTOSCAN program or data). Oscillogram traces were used to verify behavior of some measurements. These reviews indicated that the input data contained a significant amount of noise. This led to a recommendation by the AUTOSCAN Task Team that some type of noise filter be incorporated in the program. This recommendation was not implemented initially, but measurement activate/deactivate flags were incorporated during the mission that would suppress the measurements having an unusually high degree of activity. The AUTOSCAN program had the capabilities/constraints at the February 1973 time frame as shown in Table II.D-1.

A series of Mission Simulations were initiated in January 1973, which involved both MSFC and JSC. These simulations included transmission of simulated ADDT data from JSC to MSFC. Many problems were encountered with the transmission of these data, which was processed through the AUTOSCAN program as it became available. The review of the AUTOSCAN outputs from this simulation were hampered due to the lack of a nominal data base for comparison and the problems associated with the data transmission network. Problems uncovered and comments were again transmitted to the programmer/analysts for refinement of the program.

Approximately 25 percent of the 46 Special Modules requested had been programmed at SL-1 launch but none had been checked out, with the major effort expended on developing the baseline program. The computer time allotted to the AUTOSCAN program had been expected to severely limit the chances of running the Special Modules, and data users were made aware early in the program that the Special Modules would be deleted if computer time became excessive.

Multiple limits were submitted by several mission support groups for many of the analog measurements. The capability to handle multiple limit scans for a measurement was beyond the ability of the baseline analog scan program. An attempt was made to coordinate a consistent set of limits between the various requestors with the majority of the conflicts resolved; however, because there were some conflicts that could not be resolved, the decision was made to accept only the parameter limits submitted by the MSGL for his system.

The problems with the data network continued through the launch timeframe. At the time of SL-1 launch, ADDT could be transmitted, but not at the level anticipated or at a level necessary to satisfy the data requirements. The data requirements were fulfilled by relying primarily on real-time data and expanding the support provided by the Mission Operations Planning System (MOPS) terminals. While ADDT could be transmitted electronically at a reduced rate, it was primarily available only on selected batches during the early days of the mission. To expedite

Table II.D-1. Baseline Program Capabilities and Major Constraints

BASELINE PROGRAM CAPABILITIES

1. Read routine for ADDT
2. Reduce event data
 - a. Bilevels, single bit discretetes
 - b. ATM Digital Computer (ATMDC) bit pattern
 - c. ATMDC single bit
3. ATMDC and 8K backup processor
4. Switch selector processor
5. Input processor
6. Output processor
7. Limit sense, analog or ATMDC
8. Change limits by event detection
9. Deactivate measurements by event detection
10. Activate measurements by event detection
11. Key special processing by AUTOSCAN flags

MAJOR CONSTRAINTS

1. Accept ADDT
2. Programmed for UNIVAC 1108 Exec VIII computer
3. Huntsville/Slidell computer compatibility
4. Maximum of 65K word core storage
5. Modular
6. No analysis/evaluation
7. High interest areas detected/flagged
8. Intended for Saturn Workshop telemetry data
9. Limits could be changed during mission (48 hour turnaround time)
10. Execute as ADDT becomes available
11. No general purpose module for cyclic, slope of consumable data types
12. Requested units of the scanning limits must be in agreement with MSFC calibration data tape
13. Airlock and ATM telemetry data systems are run independently
14. Requested scanning limits should be in agreement with limits requested by the system's responsible office

the receipt of data, a scheme was employed whereby tapes were flown from JSC to MSFC for processing. These and other data problems impacted use of the AUTOSCAN program to a large degree. It was not until May 20, 1973 (six days after SL-1 launch) that any AUTOSCAN output became available and not until June 14, 1973 that it became available for most batches of data.

The decision to expand the support provided by the MOPS terminals to help fulfill the data requirements included installing additional terminals and manning these terminals around the clock. To help relieve the manpower problem created by this expansion of effort, the AUTOSCAN Task Team supplied four personnel to man the MOPS terminals. The evaluation of the AUTOSCAN program performance continued with half the required manpower. In the early AUTOSCAN outputs, erratic and erroneous behavior was noted on many measurements. On May 21, 1973, one week after SL-1 launch, an information sheet indicating this behavior was made available to AUTOSCAN requesters and was later supplemented by at least two more information sheets directly relating to noise.

Correlating data were obtained and reviewed and it was established that the AUTOSCAN program was accurately reflecting the input data. As a result, the AUTOSCAN output was used as a tool to research the problems of the input data, attempting to isolate the various data network problems, and to serve as a basic measure of quality for the data. In late June 1973 investigations of the data problems were finally initiated by other groups and on July 5 and 6, 1973 the first of several "data verification" tests were conducted that involved the entire data system and included review of data by JSC, Goddard Space Flight Center (GSFC), and MSFC.

The AUTOSCAN Task Team was requested to participate in these activities and represented the major part of the effort from MSFC. The review of the data from the data verification tests was somewhat limited because only data received and processed at MSFC were available. The review generally consisted of using "octal" dumps of the data for certain selected measurements and researching these data for items indicating anomalous or strange responses. Items noted by the AUTOSCAN review were further researched by using various special processing data to attempt to reach conclusions concerning the cause of the anomalous behavior noted in the data. In some of the early reviews, support of the MSGLs was enlisted to determine expected behavior for measurements and to attempt to correlate data as seen on the consoles with the ADDT data.

The initial test and subsequent review produced 36 problems or anomalous behavior occurrences (26 ATM and 10 AM). In an intercenter meeting at JSC in mid-July, seven of these items were presented and four discrepancy investigations were initiated by JSC. Late in July, in another intercenter meeting at JSC, an additional five items were presented. At this last meeting a total of eight recommendations were made by MSFC and seven of these were implemented.

The investigation made by JSC also uncovered many problems and caused fourteen Discrepancy Reports (DRs) to be generated with actions being

assigned to both JSC and GSFC. The classes of problems generally agreed with those noted at MSFC. The DRs were concerned with such things as improper handling of data by the Mission Data Retrieval System (MDRS), operational procedure problems, Decommunator/Remote Site Command Computer (DECOM/RSCC) software interface problems, Remote Site Data Processor (RSDP) software interface problems, automotive interference at Vanguard, etc. Changes were implemented to resolve these problems.

A decision was made at MSFC to delete the AUTOSCAN Analog and Event Scans and replace them with an "Events Summary Program" in an effort to process more data. The "Events Summary Program" was the AUTOSCAN program with the analog scan capability removed.

During September 1973, an additional series of data verification tests were performed. The interim work from the first verification tests, plus the resulting work from these September tests, did produce some improvement in the quality of the data. Unfortunately the effort was primarily centered on the ATM and principally on ATM Auxiliary Storage and Playback (ASAP). As a result, the quality of the ASAP data had improved considerably while ATM real-time and AM data showed virtually no improvement.

The review of the "Events Summary Program" output continued and other data were reviewed for problems. Avoid Verbal Order (AVOs) forms were submitted to obtain correlating data to research suspected problems and attempt to isolate the causes.

In mid November 1973 activities were initiated to form a "Data Quality" group that would review the incoming data using various intermediate processing outputs and provide an overall monitoring and advice function for the data processing at MSFC. Four members of the AUTOSCAN Task Team were assigned to staff this effort on November 16, 1973. Again, the primary emphasis was on the ATM ASAP data. The effort produced some improvement in the data and spotlighted numerous deficiencies in the data processing system at MSFC. The support of this effort continued through February 10, 1974, two days after SL-4 splashdown.

b. Conclusions and Recommendations. The quality of the input data for the AUTOSCAN program caused the program to produce erroneous data, resulting in an output that was more voluminous than planned. Additionally, the long lead time before the output became available decreased the usefulness of the program output to the data users. Normally a minimum of three days was required from the time data was received at MSFC until the output was distributed. Minor refinements were made to the AUTOSCAN program during the mission to improve either computer time or to reduce volume of output.

While the AUTOSCAN program did not totally fulfill its intended function due to problems beyond its control, data users classed it as a

potentially valuable tool. In view of the increasing amount of data from space vehicles as systems become more sophisticated, it is felt that a program employing the AUTOSCAN concept would be highly desirable for use with future programs.

For future programs using computer review of down-linked telemetry data similar to the AUTOSCAN concept, the following recommendations should be given serious consideration:

(1) An AUTOSCAN type of program should be an integral part of the data management system. All the data management functions - AUTOSCAN, data acquisition, data processing, data distribution, etc. - need to be integrated into a more unified organization, operating under a single management area, and, if possible, under the leadership of one principal group.

(2) Checkout and debugging of the overall data transmission system and software should be initiated early with a high degree of involvement by all associated groups. The data system must be in good operational readiness at the time of launch. It is not possible to perform adequate debugging operations on the data system after mission initiation.

(3) A rigidly controlled data base should be built for early checkout phases of the program (simulated input data tape). The behavior of each measurement on this tape should be known immediately (data values vs times, discrete occurrences vs times, bit patterns of digital measurements vs times, etc.). This would allow faster review of the outputs with problem isolation and debugging of the program before use with data of unknown quality.

3. Corona Analysis. During the period between 1961 and 1969, several space vehicles that used high voltage for power generation and electronic sensing devices experienced one or more anomalies resulting from the effects of corona. These anomalies were primarily caused by malfunction of sensitive circuits as evidenced by erroneous data, loss of data, loading of high impedance power supplies, insulation deterioration, production of noxious gases and odors, and/or eventual voltage breakdown resulting in system loss.

Based upon these past experiences and the fact that Skylab was the most sophisticated manned space vehicle to be flown, NASA/MSFC initiated a corona investigation and assessment effort to determine the susceptibility of the flight designed hardware to the effects of corona. In addition, the survey was to identify tests and analysis required to verify the need for design modifications and operational constraints procedures for the hardware.

a. Permission Analysis. Of the 437 module equipment and experiment items scheduled for flight that were surveyed, 44 items were determined to be corona-susceptible. Eighteen of these items were

identified as requiring further tests and/or analysis. Three of the 18 items were modified during prototype development to reduce susceptibility. The other 26 items were determined to be flightworthy.

(1) Susceptible Equipment. All susceptible equipment was analyzed and categorized as shown in the Table II.D-2 summary. Many items were successfully used on Apollo in applications similar to those intended for Skylab. Other items successfully passed qualification tests to prove life capability. Only six items, shown in the "RESTRICTED" column of Table II.D-2 required further effort. All items were either cleared for unrestricted use or had operational constraints procedures defined.

(2) Susceptible Experiments. All susceptible experiments were analyzed and categorized as shown in Table II.D-3 summary. Only two of the experiments shown were initially considered corona-free, but all were eventually cleared for use with imposed operational restrictions.

(3) Investigation Results. The results of the detailed analysis of susceptible equipment and experiments are shown in Tables II.D-4 and II.D-5 respectively. The recommended general mission constraints procedures for all items that were corona susceptible at launch are summarized in Table II.D-6.

b. Mission Performance. It was recommended in the Corona Investigation Final Report Revision and Addendum A (5-2935-HSV-554, dated February 7, 1973) that the AM 10-watt transmitter be energized only after the AM Truss pressure was below 0.66 N/m^2 (5×10^{-3} torr). The premission ground test data indicated that it would require at least 12 hours after SL-1 liftoff for the pressure to be at 1.5 N/m^2 (1.1×10^{-2} torr). The actual pressures in the AM truss area for the first three hours after launch were in excess of 0.66 N/m^2 (5×10^{-3} torr) and exceeded 1×10^{-3} torr for the first 14 hours. Actual pressure profile data indicated that localized pressure about the 10-watt transmitter was in excess of that for the vehicle, due to packaging which restricted a rapid depressurization as experienced by the explored vehicle surfaces.

Since the AM 10-watt transmitter was activated during this high pressure period (as predicted), corona bursts resulted, as recognized by losses in power and data. Rapid action by the ground personnel in deactivating the 10-watt transmitter and activating the 2-watt transmitter corrected the problem. The 2-watt transmitter was used until power localized pressures were reached for 10-watt transmitter operation.

On days 5 and 7, the OWS was depressurized, resulting in excessive gas being ejected about the AM/MDA/ATM external hardware. The ejected gas was far enough from the Radio Frequency (RF) components to be no hazard. As recommended, however, all future ejections were

Table II.D-2. Corona Susceptible Equipment

DESCRIPTION	LOCATION	PEAK VOLT-AGE, VOLTS	RF POWER WATTS	INITIAL DESIGN		
				FLIGHTWORTHY	MODIFIED	RESTRICTED
1. Telemeter Transmitter	AM	-	2-5	Similar Application(Gemini)	-	-
2. Telemeter Transmitters	AM,ATM	-	10-20	Life Test	-	-
3. Coaxial Switches	AM	-	2-30	Test	-	-
4. Quadriplexer	AM	-	2-30	-	-	Test Requested
5. EVA Lights	AM	600	-	Test and Analysis	-	-
6. Tracking Light	AM	1,750	-	-	-	Insulation Failed
7. Fire Detector Sensor	AM,MDA	15,000	-	-	-	-
8. Latch Release Firing Unit	OVS	355	-	Sealed Analysis	-	-
9. Switch Selector	AM	2,300	-	Similar Application(Apollo)	-	-
10. Pulse Sensor	ATM	1,500	-	Similar Application(Apollo)	-	-
11. EBW Firing Unit	ATM	1,500	-	Similar Application(Apollo)	-	-
12. Star Tracker Opto-Mech Assy	ATM,OVS	1,500	-	Similar Application(Apollo)	-	-
13. Camera Control Unit	ATM	-2,000	-	Similarity Test	-	-
14. TV Camera LLL	ATM	450	-	Test	-	-
15. Vidicon Camera	ATM	8,000	-	Test	-	-
16. Portable TV Camera	ATM	450	-	Test	-	-
17. Two-Channel Multicouplers	OVS	8,000	-	-	TBD	TBD
18. Coaxial Switches	ATM	-	10-25	Test	-	-
19. Directional Coupler	ATM	-	10-25	Test	-	-
20. Antenna Panel Assy Model 316	ATM	-	10-20	Test	-	-
21. Deployable Dipole Antenna Model 231	ATM	-	10-20	Test	-	-
22. Ion Gauge	ATM	1,100	-	Life Test	-	-
23. Coaxial Switches	IU	-	15	Similar Application(Apollo)	-	-
24. C-band Transponder	IU	400	800	Similar Application(Apollo)	-	-
25. CCS Power Amplifier	IU	1,800	15	Similar Application(Apollo)	-	-
26. RF Assembly (P1 & F1)	IU	500	15	Similar Application(Apollo)	-	-
27. Interior Lights	MDA,OVS	310	-	Test and Analysis	-	-
28. Inverter-Lighting Control Assembly	MDA	380	-	-	Redesign	Test Requested
29. ATM C&D Panel	MDA	8,200	-	-	-	TBD
30. Proton Spectrometer	MDA	1,100	-	-	Vented	Test Requested

Table II.D-3. Corona Susceptible Experiments

EXPER- IMENT	DESCRIPTION	LOCATION	PEAK VOLT- AGE, VOLTS	FLIGHTWORTHY	INITIAL DESIGN
				KNOWN	EXISTING PROBLEMS
M171	Metabolic Activity	OWS	4,200	-	-
M512	Material Processing Facility	MDA	28,000	-	High Voltage Tracking
M551	Metals Melting Experiment	MDA	-	-	-
M552	Exothermic Brazing Experiment	MDA	-	-	-
M553	Sphere Forming Experiment	MDA	-	-	-
M554	Composite Casting Experiment	MDA	-	-	-
M555	Gallium Arsenide Crystal Growth Experiment	MDA	-	-	-
S054	X-Ray Spectrographic Telescope	ATM	3,250	-	-
S055A	UV Scanning Polychrometer/Spectroheliometer	ATM	4,000	-	JSC Voltage Dropouts
S056	X-Ray Telescope	ATM	2,300	-	JSC Voltage Dropouts
S073	Gegenschein/Zodiacal Light	OWS	3,800	-	-
S082B	UV Spectrograph	ATM	1,300	Test	-
S150	Galactic X-Ray Mapping	IU	2,100	-	Broken Membrane
S190B	Earth Terrain Camera	OWS	120AC	Test and Analysis	-
S191	Infrared Spectrometer	MDA	3,000	-	-
S193	Microwave Radiometer/Scatterometer	AM	11,000	-	Insulation Failed
T003	In-Flight Aerosol Analysis	OWS	1,000	-	5 psia Test Required
T027	ATM Contamination Measurement	OWS	3,800	-	Special Test Requested
T031	Spacecraft Surfaces Spectroreflectometer	AM	-	-	-

Table II.D-4. Equipment Detailed Analysis Result Summary

ITEM	EQUIPMENT	PROBLEM	RESULTS
1.	Quadriplexer	Corona at pressures between 133 N/m ² and 1.33 N/m ²	<ul style="list-style-type: none"> ● Limit power to 1.6 watts. ● Cycle the transmitter "off" and "on" if corona occurs.
2.	Tracking Light	High voltage pulse line	<ul style="list-style-type: none"> ● Operate normally. If corona appears, turn off set #1 and use set #2. ● Outgassing will be sufficient for normal operation on Skylab III and IV.
3.	TV Cameras	High voltage circuit	<ul style="list-style-type: none"> ● Corona recognized by bars and flashes on the monitor.
4.	Low Light Level Portable	High voltage circuit outgassing	<ul style="list-style-type: none"> ● If corona appears turn "off" for 15 minutes to complete outgassing. ● If corona persists turn "off". Allow 72 hours vacuum soak before re-energizing with high voltage.
5.	ATM Control and Display Panel	High voltage monitors	<ul style="list-style-type: none"> ● Corona recognized as bars and flashes. ● Corona will appear if operated at pressures less than 3.2 x 10⁴ N/m². ● Oxygen only atmosphere may require pressurization to 3.7 N/m².
6.	Proton Spectrometer	High voltage open circuitry	<ul style="list-style-type: none"> ● Outgassing ports were added to decrease pressure more rapidly. ● Corona recognized as noisy output. ● In case of corona turn the unit "off" for 72 hours to allow sufficient outgassing.

Table II.D-5. Experiments Detailed Analysis Result Summary

ITEM	EXPERIMENT NUMBER	PROBLEM	RESULTS
1.	M512	28-kv circuits	<ul style="list-style-type: none"> • The electrodes must be well evacuated to less than 1.33×10^{-3} N/m² prior to high voltage application. • Power supply has passed all high voltage tests.
2.	S055A	Power detector unit-corona	<ul style="list-style-type: none"> • Corona is recognized as pulses of noise in the output data. • Recommend operation of detectors with the ATM port closed to measure dark counts periodically. • In case of corona turn the affected PDU "off" for 72 hours to outgas.
3.	S056	High voltage power supply	<ul style="list-style-type: none"> • Corona is recognized as impulses in the output data. • Corona most probable within first week of operation. • Temperature increases will increase corona probability. • If corona appears turn the unit "off" for 72 hours and then re-energize.
4.	S073/ T027	Outgassing time Temperature rise High gain operating voltage	<ul style="list-style-type: none"> • Outgassing time at least 12 minutes. • Corona appears as increased background noise. • Switch to lower gain or turn "off" for 10 to 15 minutes to complete outgassing or cooling. • Continuous operation at "Low" and "Medium" gain. • "High" gain operation may be limited to approximately 40 minutes due to temperature increase.
5.	S193	11-kv power supply	<ul style="list-style-type: none"> • The altimeter was not tested for corona. • If corona appears in the power supply it will probably result in an arc-over. • If corona occurs on the high voltage terminals or wiring, outgassing will be required. • Outgassing can be accomplished by allowing the unit to outgas for an additional 72 hours.

Table II.D-6. Recommended Mission Constraints

<u>PROBLEM</u>	<u>CONSTRAINT</u>
<ul style="list-style-type: none"> ● Outgassing during first 12-hours of flight. 	<ul style="list-style-type: none"> ● 2-watt transmitter operation for one-half hour. ● 10-watt transmitters may not operate without corona for first hour. ● All ATM and Earth Resources Experiment Package (EREP) high voltage experiments must be turned "off" for at least 3 days.
<ul style="list-style-type: none"> ● Depressurizing the MDA, AM and OWS 	<ul style="list-style-type: none"> ● High voltage items must be turned "off" and not operated for one-half hour after pressure is stabilized at $3.2 \times 10^4 \text{ N/m}^2$ (4.7 psia) or higher. ● When pure oxygen is substituted for an oxygen-nitrogen mixture the oxygen pressure should be 15% higher than normal. That is, $3.7 \times 10^4 \text{ N/m}^2$ (5.2 psia).
<ul style="list-style-type: none"> ● Excessive leaks or reaction control gas emissions toward an operating unit 	<ul style="list-style-type: none"> ● Some high-voltage units may become noisy and should be turned "off" immediately. ● The noisy units should be left "off" for one hour following the gas emission leakage flow, so the unit can again depressurize.
<ul style="list-style-type: none"> ● Noisy Output 	<ul style="list-style-type: none"> ● Noise can result from corona. Turn the unit "off" for one hour to allow the circuit to outgas and cool. Turn the circuit "on" and monitor noise. Determine if corona is present and reduced after one minute of operation.
<ul style="list-style-type: none"> ● Persistent Corona 	<ul style="list-style-type: none"> ● Outgassing of potted circuits may take as long as one month. It is advisable to operate the unit periodically to determine if the corona is reducing as a function of time.
<ul style="list-style-type: none"> ● High Temperature Operation 	<ul style="list-style-type: none"> ● Insulation is more subject to corona at high temperature due to increased outgassing and reduced dielectric strength. ● Turn the system "off" as soon as corona pulses occur.

at a reduced rate, thus eliminating any possibility of high voltage equipment corona related or induced problems.

Six days after SL-1 launch, a meeting was held at MSFC to discuss the corona susceptibility aspects of adding a solar shield to the OWS for thermal control. Since the shield was to be a large metallic sheet, it would eventually become charged by the space plasma. This charge would be at a different potential than the OWS tank skin. This effect, coupled with the solar wind effects, would cause the shield to move toward the tank skin. At the critical pressure-spacing product, corona bursts could have occurred. Construction of the shield had two corona reducing features:

- A mylar insulating layer was placed between the metallic portions of the shield and the OWS tank skin; and
- Nonconducting nylon ribbing was used.

In addition, only aluminum foil was used (1/4-mil mylar with very thin aluminum (Al) coating) and the conductive thermal control paint (Sl3G) would face the sun. Aluminum rods, used to support the shield, would collect the charge on the shield surface and dissipate it to an insignificant level before reaching the tank skin.

c. Conclusions and Recommendations. Early development of corona specifications defining pressure and voltage design and test criteria, eliminates the need for much of the postdesign tests and analyses expended for Skylab. However, analyses by high-voltage experts armed Skylab managers with detailed facts regarding Skylab equipment and experiment hardware, which resulted in a corona-free mission.

Where equipment cannot be designed or protected against corona occurrences, it is imperative that predefined operational constraints procedures be strictly observed.

4. Other Special Engineering Analysis. Other special engineering analysis efforts were performed on Skylab. Several significant studies were safety oriented and are summarized in Section V.C in this report. Studies which were performed as part of a particular system development are summarized in the respective system paragraph in this report.

E. Structural and Mechanical Systems

The initial AAP program considered such items as experiments on space-erectable or expandable structures, deployable booms and mechanisms, data recovery vehicles from orbit, development of new docking devices, spacecraft on tethers, and artificial gravity spin-up of the entire Orbiting Assembly (OA). Structural dynamics analyses were made on flexible, 200-ft booms with low frequencies; small deployable spacecraft tethered by long cables to the workshop; and also the dynamics of large spinning assemblies with the CSM attached by cables or booms.

By December 1966 the concept of an MDA, which was considerably larger than the AM, was accepted as baseline for all structural studies. It should be noted that a shorter MDA or AM with a somewhat larger diameter was proposed; however, the former concept was accepted. Structural modules identified and accepted as baseline to the program were:

- LEM - Lunar Explorer Module to be used as unmanned carrier/docking device for ATM.
- ATM - Apollo Telescope Mount.
- MDA - Multiple Docking Adapter with one axial and four radial docking ports (two radial ports were to be used for emergency or convenience only).
- AM - Airlock Module for transition from MDA to S-IVB through the Spacecraft LEM Adapter (SLA).
- SLA - Spacecraft Lunar Module Adapter.
- S-IVB - "Wet" Second Stage of S-1B.
- BOOM - 100-ft boom (originally considered being deployed from S-IVB before the MDA concept).
- RM - Resupply Module
- LM&SS RACK - Lunar Mapping and Scientific Survey rack.
- SOLAR ARRAYS - Only for the ATM.
- CABLES - For possible reeling-out of ATM from LEM or CSM from S-IVB.

It should be noted that the requirement for an artificial gravity of at least $1/6$ was baseline at this time.

The principal activity was addressed to hard-tethered (boom) and soft-tethered configurations, design of MDA, and mission requirements. By July 1967 the following structural activity had been completed:

<u>STUDY</u>	<u>CONCLUSION</u>
Cable Dynamic Studies for Configurations of Soft-Tethered ATM, CSM, and LEM	Discarded
S-IVB to be used as Wet Workshop at 260 Nautical Mile(n mi) Orbit using Saturn 1-B (S-1B)	Accepted
Unmanned Docking of LEM/ATM to MDA	Accepted
Boom Configuration, Hard-Tether LEM/ATM	Backup to System

By May 1968, MDA longeron design was frozen and all work on the Lunar Module (LM) and ATM was stopped due to design changes. This was primarily in the subsystem area but also due to structural load problems. Other changes included the following:

- Redesign of SLA due to acoustics,
- ATM canister load-carrying (had been nonload-carrying) and attachment of packages,
- Refinement of orbital/launch locks (had been primarily a one-lock system),
- Structural beef-up of LEM at LEM/ATM interface,
- Problem identified for latch loads North American Rockwell (NAR)/JSC stated possible 350-400K loads, but probably were conservative,
- OWS-Solar Array System (SAS) hinged to allow always face sun,
- Unmanned docking of LEM/ATM,
- Deletion of two radial ports: LEM/ATM port with crew installed probe; and 90 degrees away, spare CSM port with drogue but not electrical, due primarily to mission cutdown and weight savings,
- No testing requirement for RM.

Structural work proceeded from definition of load programs. For dynamics, this included docking, latching, acoustical, and design loads for experiment and commodity packages.

By April 1969 the OWS structural model was still undefined and docking latch loading was appearing as a real problem. By May 1969, influence coefficients for the axial port were completed with MDA beam stiffness with radial port influence. A sophisticated docking program was also deemed necessary.

In the summer of 1969 the dry workshop decision was made and the LM eliminated from the program. The final configuration was firmed by November 1969 using a folding truss to rotate the ATM rack 90 degrees after orbit injection.

1. Design Requirements. After advent of the dry workshop, structural design philosophy reflected over-design of the structure to eliminate structural testing. The policy was then defined in the CRS that new structure designed for the Skylab payload would be stress-analyzed with a factor of safety of 2 on yield and 3 on ultimate and therefore no static tests of the structure would be required. Also, because previously designed structure was to be used, it was stated that factors of safety of 1.1 on yield and 1.4 on ultimate would be used in the stress analysis on manned structures. These limits were confirmed by static testing and factors of safety of 1.1 on yield and 1.25 on ultimate on unmanned structures. All module contractors were requested to use these guidelines in writing their CEI specifications.

These requirements were met in the design of the MDA and the PS. The AM structure was an existing design negotiated early in the AAP when a factor of safety of 1.36 on ultimate and no requirement for yield were permitted. Contract waivers and deviations would be allowed, recorded, and approved in Appendix K of the CRS. Also, verification of strength was made by static tests of the AM/MDA on the original static test articles. Waivers also granted on subsequent design modification to this test structure, therefore, new overall static tests were not run.

a. Design Criteria Documents

(1) Cluster Requirements Specification. A single document that identified the design criteria for all contractors. This document included the authority to grant deviations to contractors with structures designed to different criteria. Thus, Appendix K to the CRS became an official record of deviations.

(2) IN-ASTN-AD-70-2. Served as the preliminary loads criteria reference. It was a first-cut analysis to provide data for initial design of the low-frequency primary structure. It consisted of the dynamic analysis of a mass-spring model and it served the purpose of getting the program started by supplying design launch loads. Later, in June 1972, an analysis was begun that included the entire Skylab payload using refined models of each module. Good correlation was obtained from this analysis. The document also provided uncoupled and longitudinal loads.

(3) IN-ASTN-AD-70-1. The loads criteria document for all internal and external components mounted on Skylab structure. The document provided the initial criteria for the design of packages and other components. The analysis considered the weight of each component and where and how it was mounted; i.e., the MDA was divided into eight zones and loads were specified for longeron or frame-mounted packages.

It was found later that the loads specified in the document were a good base for preliminary design. Some exceptions were uncovered as a result of acoustical testing that showed the criteria used in some

components were too low. A requalification test had to be applied in these instances.

The shock criteria were questioned by JSC as too conservative; testing at MSFC verified the criteria.

In some cases, deviations to the criteria were granted where detail analysis of the zone would show conservatism in the loads.

(4) IN-ASTN-AD-71-10. Published later to cover orbital loads as they apply to all structures on the cluster.

2. Functional Description. The following paragraphs describe the history of each Skylab module during its development. Vibro-acoustical tests were performed by JSC on three Skylab assemblies. The first assembly tested was the OWS Dynamic Test Article. The Payload Assembly (PA) was tested in two configurations; launch and orbital. The launch configuration consisted of the Fixed Airlock Shroud (FAS), PS, AM, MDA, Deployment Assembly (DA), and ATM. The orbital configuration was comprised of the FAS, AM, MDA, DA, a docked CSM, and a deployed ATM with no solar arrays. The results of these tests are discussed in the following paragraphs. In addition, static testing was performed on some of the individual modules and subassemblies. Descriptions and results of these tests are also given in the individual module discussion.

a. Payload Shroud. The PS provided: an aerodynamic fairing; a structural support for the ATM during launch; an environmental shield with purge capability to maintain positive internal pressure for protection of enclosed modules, and a noncontaminating separation and jettison system. From a variety of proposed PS configuration concepts, the two configurations selected for detail evaluation were:

- (1) Over-the Nose, and
- (2) Segmented Separation.

The Over-the-Nose shroud was to be jettisoned axially, with or without rails, using thrusters. The basic configuration for the concept was applicable only to the WWS. The Segmented Separation concept contained four 90-degree segments to be pyrotechnically severed and jettisoned laterally on orbit (see Figure II.E-1). Both configurations were technically feasible and the primary reason for selecting the segmented configuration was programmatic, based on cost and schedule.

The split shell had a potential advantage that deserves mentioning for possible future application. If needed, its design would be translatable to separation of the PS during ascent and from the standpoint of performance, recontact on orbit would not be a problem. An important feature of the segmented concept used in the Flight Article was the pyrotechnic system used to separate the shroud. Reliability

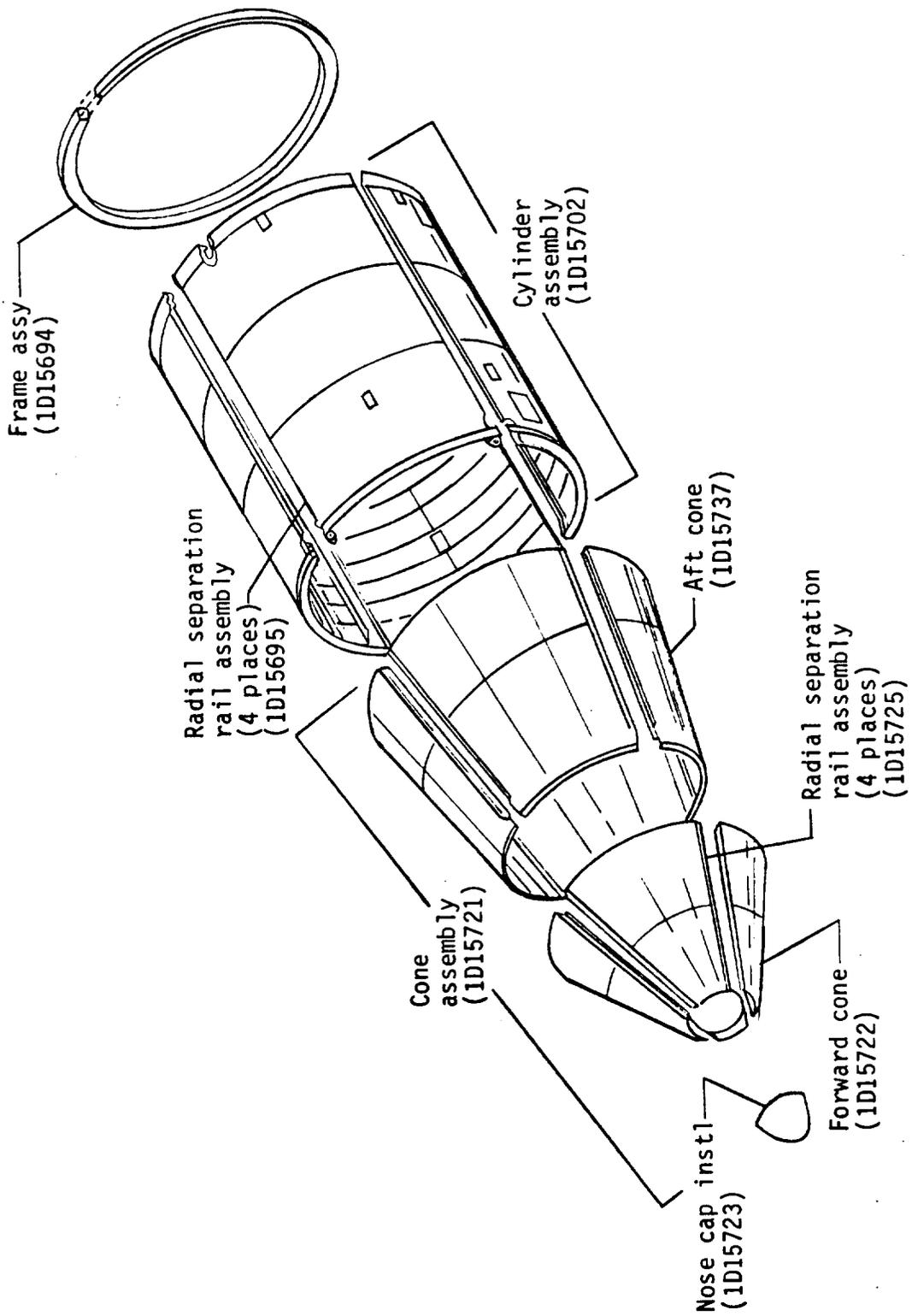


Figure II.E-1. Payload Shroud Major Structure Breakdown

was proved to be superior for all the fragments induced by its operation were contained and disposed of, thus preventing contamination of the payload.

The design criteria called for high factors of safety of 2.0 and 3.0 with no test; therefore a conservative, simplified analysis was performed on the structure. Testing was limited to ATM support areas, jettison-separation concepts, and the vibro-acoustical test on the PA (refer to paragraph II.E.2.j for further discussion). The tests demonstrated completely satisfactory performance. The analysis verified the integrity of the structure for the design flight loads.

b. Deployment Assembly. The DA rotated the ATM 90-degrees and supported it in the orbital configuration (see Figure II.E-2). The assembly did not have a static test and a factor of safety of 3 was used in the analysis. Of particular importance was the functional test to demonstrate the deployment of the 25,000-pound ATM. An air-bearing system was designed to simulate the zero-g environment. A low energy spring/cable package deployed the ATM. A unique spring-loaded latch mechanism locked the ATM in the deployed position (see Figure II.E-3). Camming action retracted the latch as the ATM/DA approached the deployed position. Just before the ATM/DA reached the deployed position, camming action and spring force preloaded the latch which eliminated latch movement due to loads generated by the Thruster Attitude Control System (TACS) firing. A ratchet locked the cam, latching the ATM/DA in the deployed position. During launch, the ATM was attached to the DA through four support points with the rigidizing mechanisms in the floating position. Following PS separation, the springs of the rigidizing mechanism retracted and rigidized the ATM to the DA interface (See Figures II.E-4 and II.E-5).

A stress analysis on primary structure was performed and is documented in the Strength Summary Report, 10M33111. The adequacy of the structure to carry design loads was demonstrated by this analysis. The DA was also included as part of the JSC Vibro-acoustical Analysis. (Refer to paragraph II.E.2.j for further discussion).

c. Multiple Docking Adapter. The MDA evolved from the original 1966 version of 65 inches in diameter by 38 inches in length to the final module of 120 inches in diameter by 163 inches in length (See Figure II.E-6). Some of the structural features required in transforming the MDA from the WWS configuration to Dry Workshop (DWS) will be discussed in the following paragraphs.

The longerons were designed to accommodate equipment that was to be transferred to the OWS. The equipment had to fit through the AM/OWS hatch and was relatively light. When the change to the DWS occurred and the EREP experiments were added, permanent equipment such as film vaults, experiment packages, and the ATM Control and Display (C&D) Console were installed in the MDA. The heavier weights of the equipment, as well as higher CSM docking loads, prompted major redesigns in the

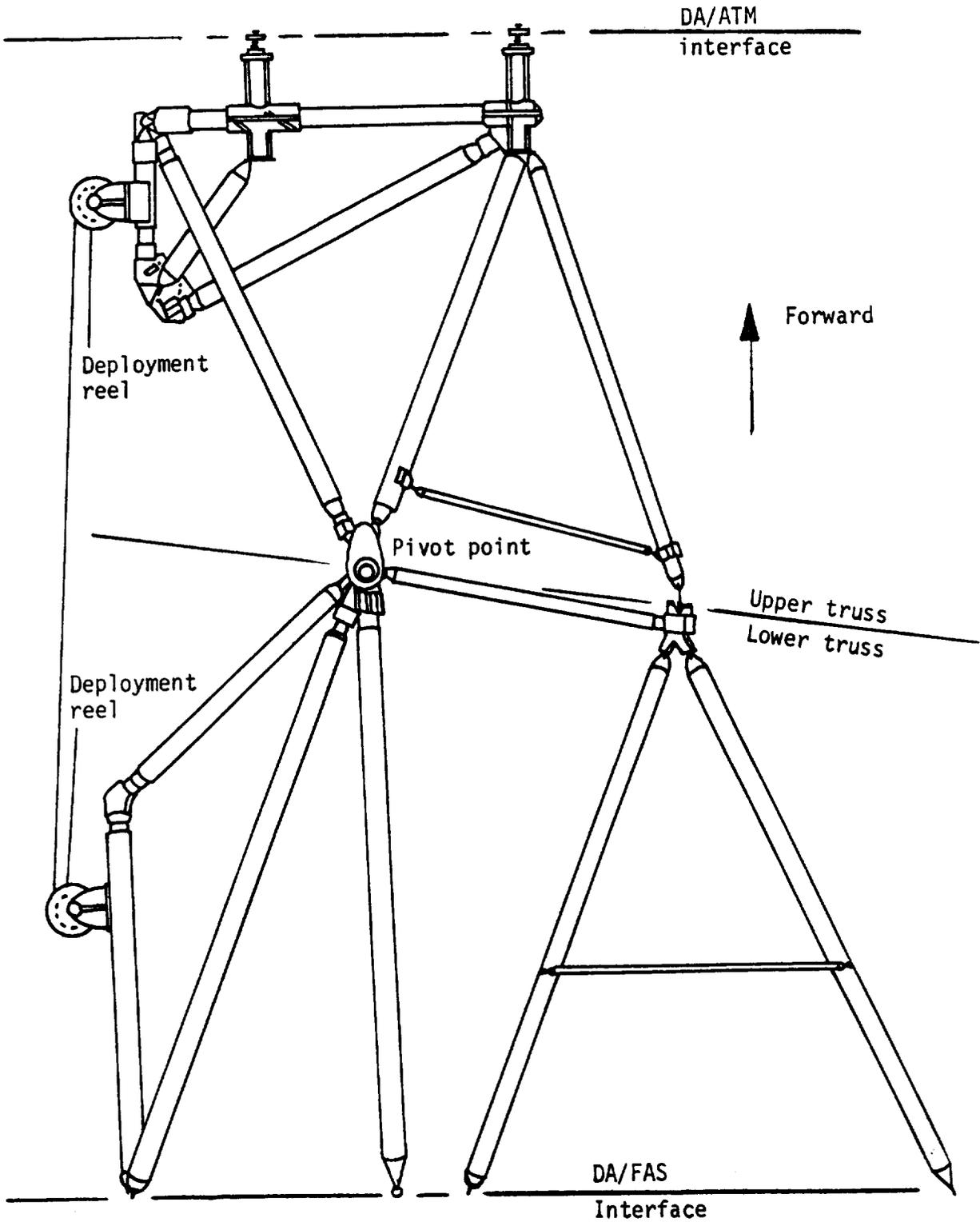


Figure II.E-2. DA in Launch Position

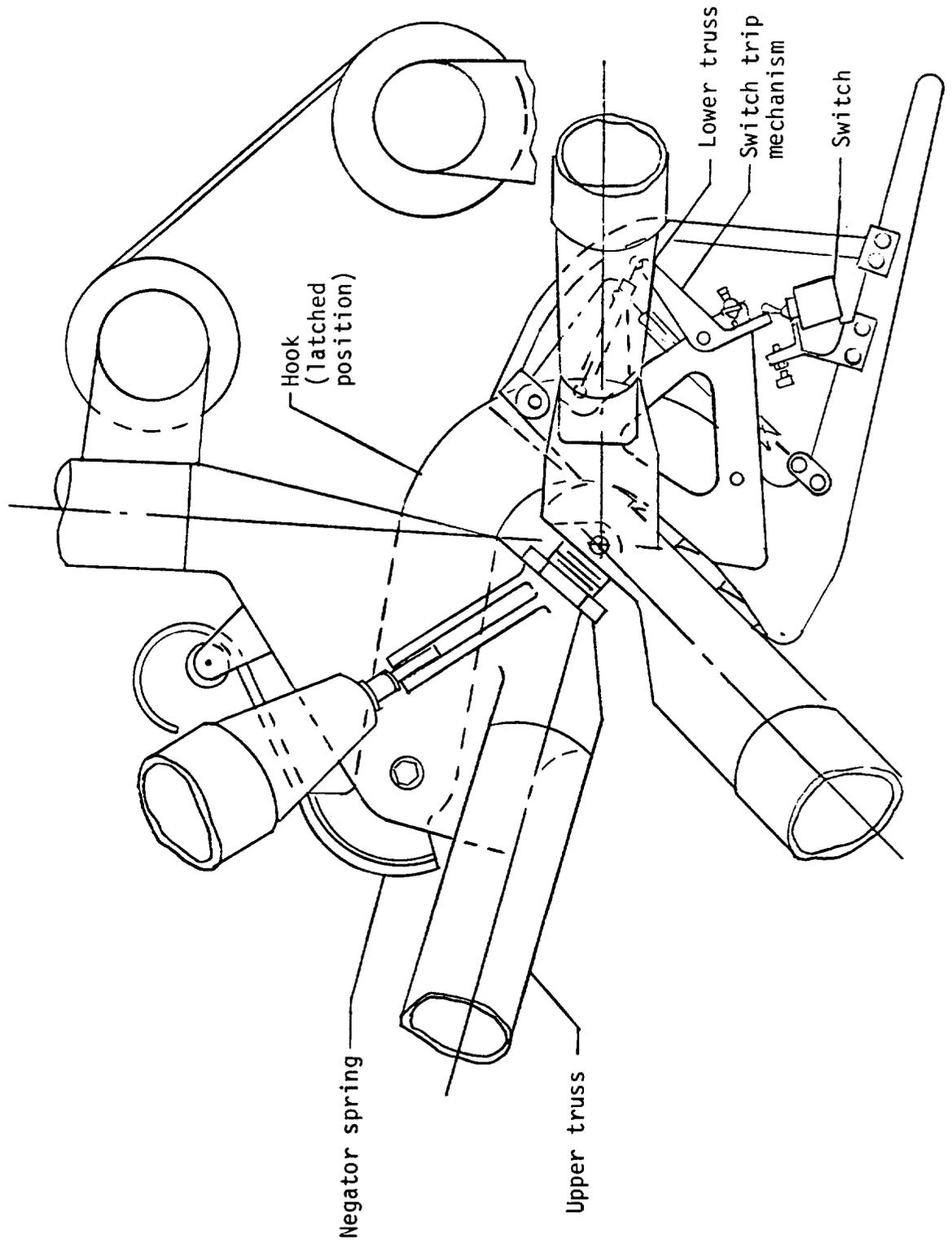


Figure II, E-3. DA Latching Mechanism

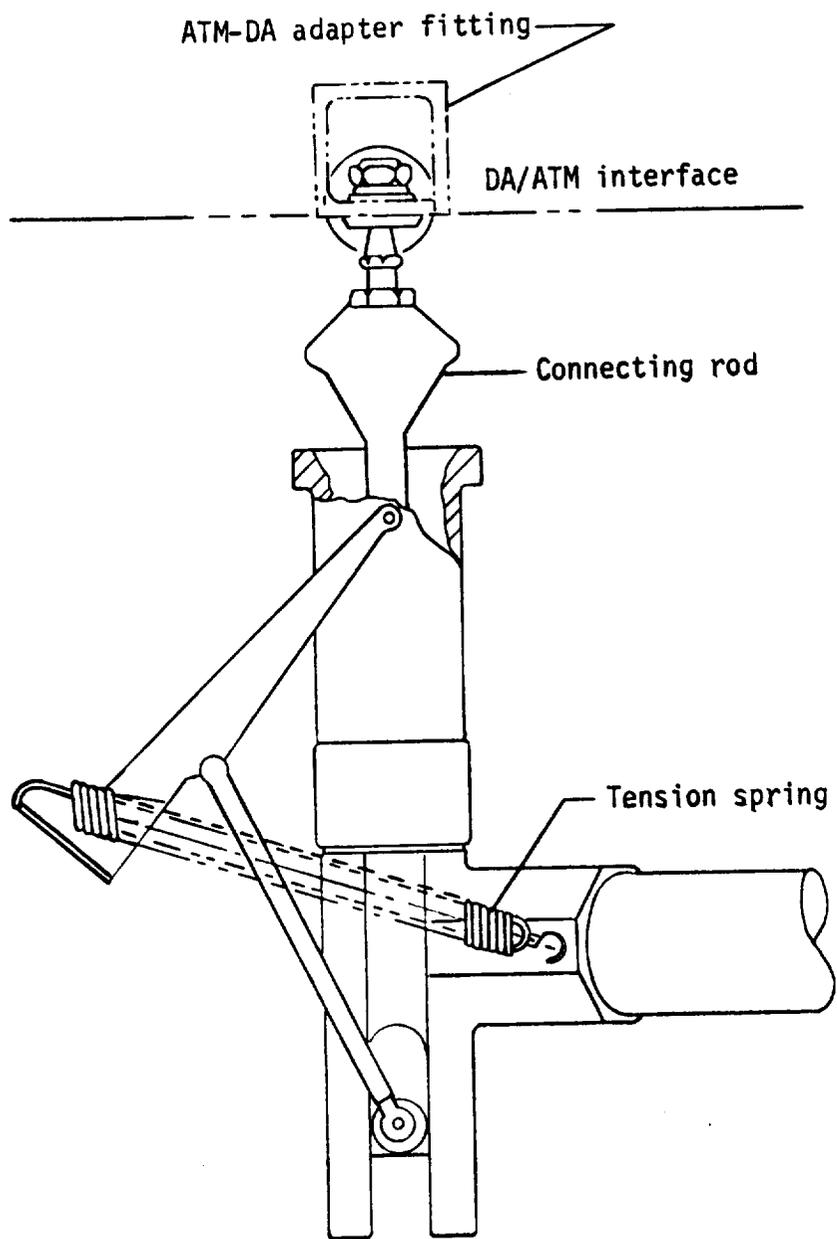


Figure II.E-4. Floating Position of the Rigidizing Arm
II-62

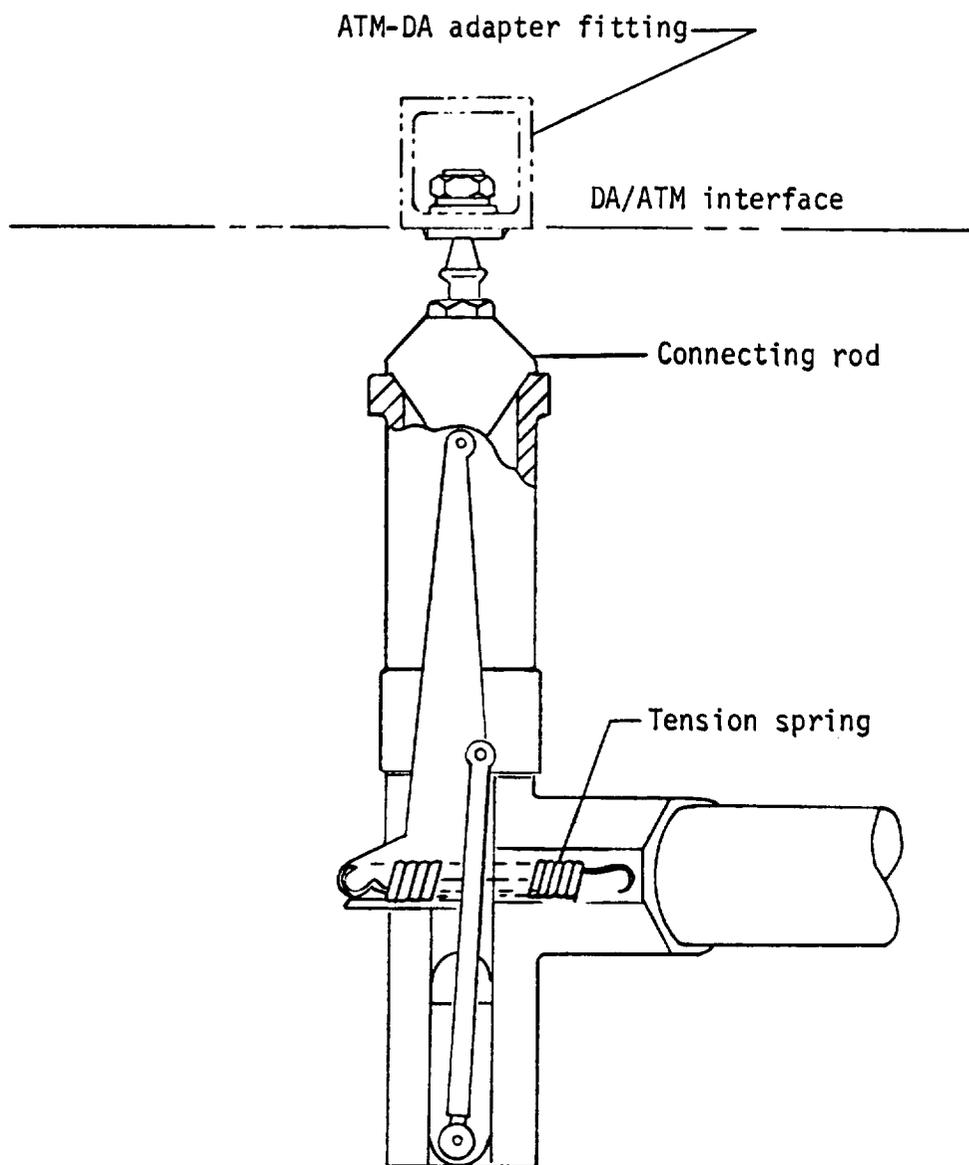


Figure II.E-5. Rigidized Position of the Rigidizing Arm
II-63

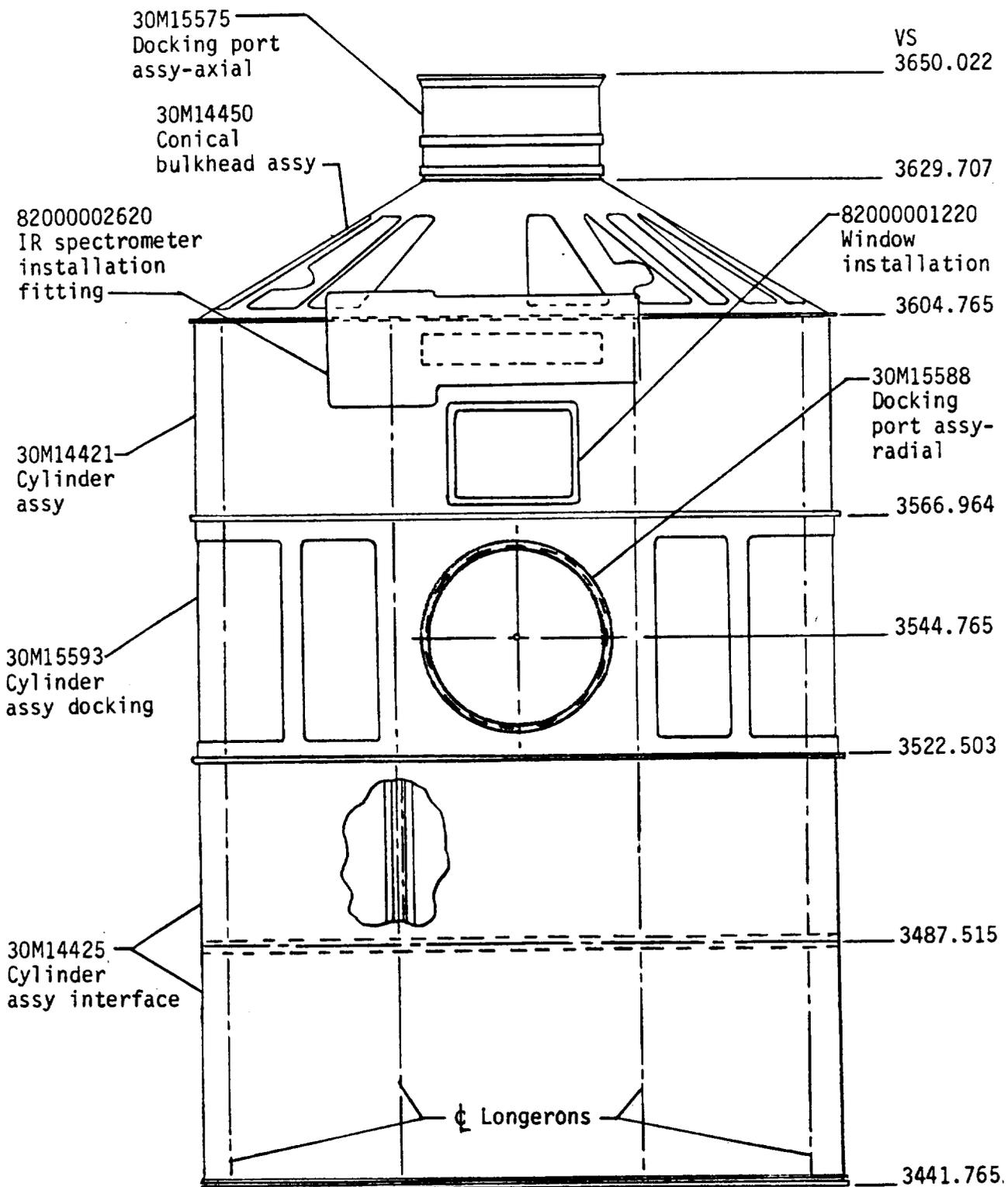


Figure II.E-6. MDA Overall Configuration

structure. The longerons had to be reinforced with longitudinal splices; the docking port frames were strengthened; and an intermediate frame was added between the ports and the Structural Transition Section (STS) interface frames. A support truss for the S194 L-Band antenna for EREP was added in 1971 in the outside shell.

The MDA was subjected to both static and dynamic tests. The dynamic test consisted of the static test article with no internal pressure. It was subjected to three phases of test, i.e., acoustical, low frequency vehicle dynamics, and modal surveys. The objectives of the dynamic test were to verify the structural assembly and its design criteria; to obtain modal response and impedance data, and to qualify the hardware for flight. The test was conducted at JSC as part of the PA. As a result of this test, weight classifications in two environmental subzones were changed, nine new environmental subzones were added, and no component requalification was required.

The static test consisted of subjecting the MDA shell to nine loading conditions. The MDA was tested to proof and leak pressure, to pressure and docking and latching loads, and to local loading conditions. The objective of these tests was to verify the structural integrity, to determine deflections and stresses, and to verify analytical methods. No structural failures occurred during the dynamic and static tests and the structural integrity of the MDA was demonstrated. Extensive analysis was performed to substantiate the design of the MDA.

d. Apollo Telescope Mount (ATM). This module was designed to accommodate solar astronomy experiments, provide the SWS or OA with attitude control and partial electrical power. It consisted of a rack, an experiment canister, four solar arrays, a C&D console housed in the MDA, and supporting subsystems (See Figure II.E-7).

Originally, the ATM Rack had the only SAS. It had an Orbital Lock System that was retractable. The launch configuration was inverted from the Skylab mode, with the solar end facing aft to the S-1B launch vehicle. The CSM was to dock to the LM/ATM, pull it out, and then insert it in orbit and let it dock to the WWS MDA. After the decision to change to DWS, some design changes came about because of inverting the launch mode and the higher environments from S-V vehicle.

The ATM was subjected to vibro-acoustical testing at JSC. As a result of this test the test criteria were increased in two environmental subzones. Requalification test was recommended for the Control Moment Gyros (CMGs). Other components were not requalified. Also, launch engine shutdown sequence was changed from 4-0 to 2-2. Static testing was performed on single structure and is described next.

e. Rack. This structure was originally conceived as a universal payload support system. There were three or four payloads under consideration. The first payload was Project Thermo that, coupled with the requirement to support the LEM Ascent Stage, was responsible for

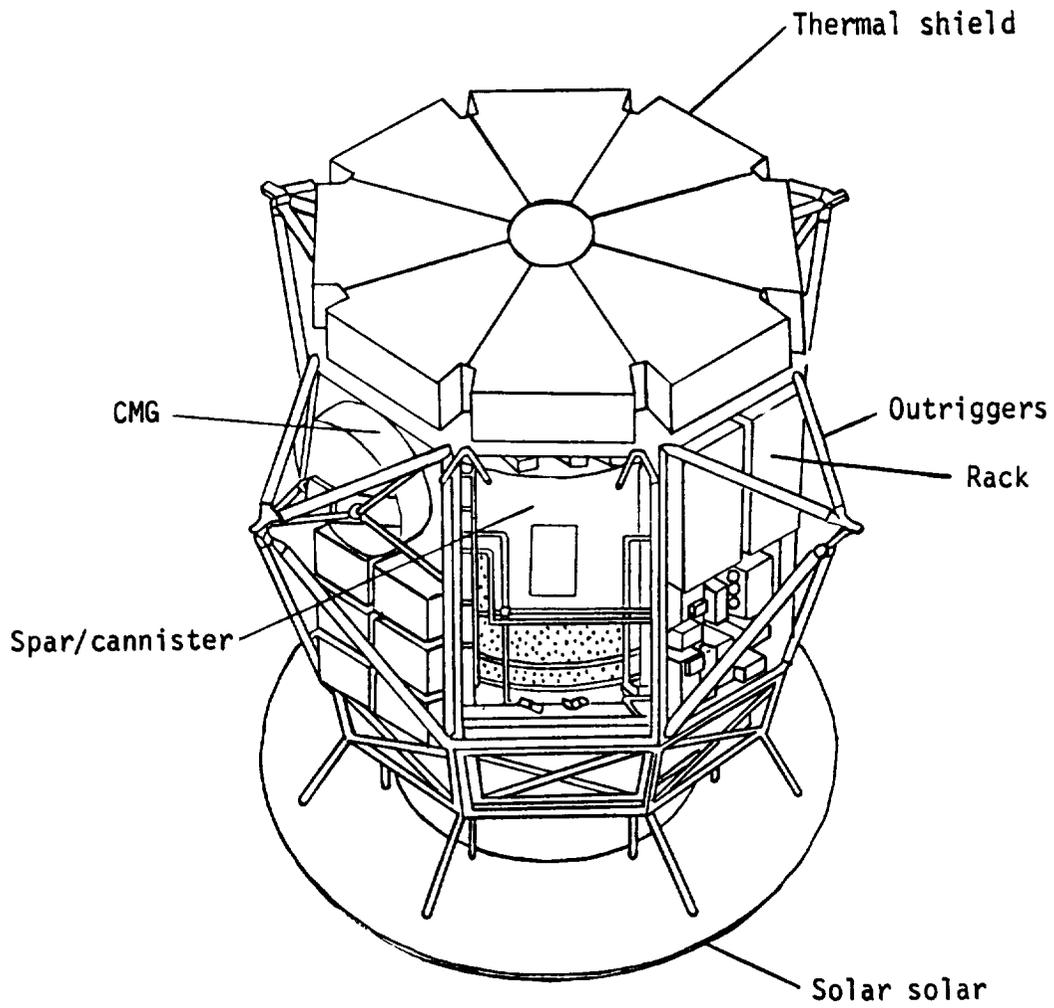


Figure II.E-7 ATM Less Solar Array Wings

dictating the Rack's octagonal shape. Other payloads included the LM&SS or Department of Defense (DOD) classified payload. Each different requirement imposed on the single structure dictated the design of separate portions of the rack, resulting in an over-designed assembly for the Skylab mission. At first, the rack had a truss configuration made from vertical beams, upper and lower rings, and diagonal members. Later, shear webs were added to the panels behind the outriggers to support the CMGs. As black boxes were added to the other panels, shear webs were also installed there. Another late addition was the Solar Array Support Ring for support of the solar arrays and to provide hard points for ground handling. Original design included an Extra Vehicular Activity (EVA) strut as one of the diagonals. This strut was required for launch loads and was designed to move out of the way with the aid of a pyrotechnic device when in orbit. Because of being a single-point failure item it was removed and the structure was proved adequate with minor changes. The structural integrity of this assembly was verified by test and analysis. The rack was subjected to transportation and flight loads with successful results.

f. Spar/Canister. This center package supporting the ATM experiments consisted of a cruciform spar evolved by the cylindrical canister. The spar was made from one-inch-thick aluminum plate to satisfy the requirements of the ATM experiments Principal Investigators (PIs) for an optical bench. When the weight was found to be excessive, about 40 percent of the material was removed with 2-inch diameter lightening holes. Originally, the center package was attached rigidly to the rack; the pointing requirement within the package came later. The structural integrity of this assembly was successfully verified by test and analysis. The spar/canister was tested to flight and transportation loads.

g. Cable Tray. The structural integrity of this assembly was verified by test and analysis. During the static test a failure was experienced on one of the fittings. Redesign and retest demonstrated the integrity of the structure. This was the only failure experienced by any ATM component.

h. Gimbal Ring Assembly (GRA). The requirement was to have a rigid support during launch and a flexible, frictionless system on orbit. The concept of gimbal rings with flexible actuators for pivots fulfilled this requirement. The structural integrity of this assembly was demonstrated by test and analysis.

i. Solar Arrays. The Solar Array structure was subjected to static testing by applying limit design loads for the launch and orbital configurations. For the orbital configuration, the test had to be stopped shortly before it was planned for the in-plane loading condition due to excessive deformation. Because of the conservative load the structure was not redesigned. The structural integrity of the assembly was also demonstrated by extensive analysis.

j. Airlock Module (AM). The AM was required to provide:

(1) A habitable, interconnecting pressure vessel between the MDA and the OWS,

(2) The atmospheric nitrogen supply,

(3) Intervehicular activities (IVAs) support,

(4) An airlock to support EVAs, and

(5) Structural mechanical equipment to support the various functional systems (See Figure II.E-8).

The as-flown AM was a carry-over from the WWS configuration to Skylab. At the time of change-over, one of the four AM trusses had a removable link; two others were changed to this configuration to allow mounting of six nitrogen bottles on the three removable link trusses. The MDA interface ring was strengthened and gussets were added to the STS stringers. Other modifications such as penetrations, welds, and revised rivet patterns were also accomplished.

The requirements for this structure grew through the evolution period resulting in three elements, i.e., the STS, the tunnel, and the trusses. Of outstanding design value were the film transfer booms. These tubular elements stored in the FAS extended 25 feet allowing the transfer of film cassettes from the EVA hatch to the ATM EVA station and back. The flexible tunnel connecting the AM with the OWS was designed to provide the continuity of the pressurized passageway between the two modules without transferring any loads. Four double-pane windows were installed in the STS with each pane capable of containing the differential pressure of the cabin.

Structural integrity of the airlock tunnel and STS was demonstrated with Static Test Article No. 1 vehicle mated to the Static Test MDA. The structure was subjected to 12.4 psid and to ultimate load simulating WWS launch and ascent loads. The launch and ascent loads for the DWS configuration were later verified by analysis as reported in "Verification of J-1 Launch and Ascent Structural Capabilities Based on Evaluation of STA-1 Static Test Results", McDonnell Douglas Astronautics Company-Eastern Division (MDAC-ED) report E-0517. Structural capability for subsequent weight increases was verified by analysis and reported in "Effect of AM/MDA Properties Change on AM Structural Capabilities", MDAC-ED report E-0654. The AM was also subjected to vibro-acoustical testing. The following were recommended for the AM, PS, DA, and FAS: an increase in the test criteria in eleven environmental subzones (three new ones were added); special environmental criteria were established for seven components, and four components were recommended for requalification tests.

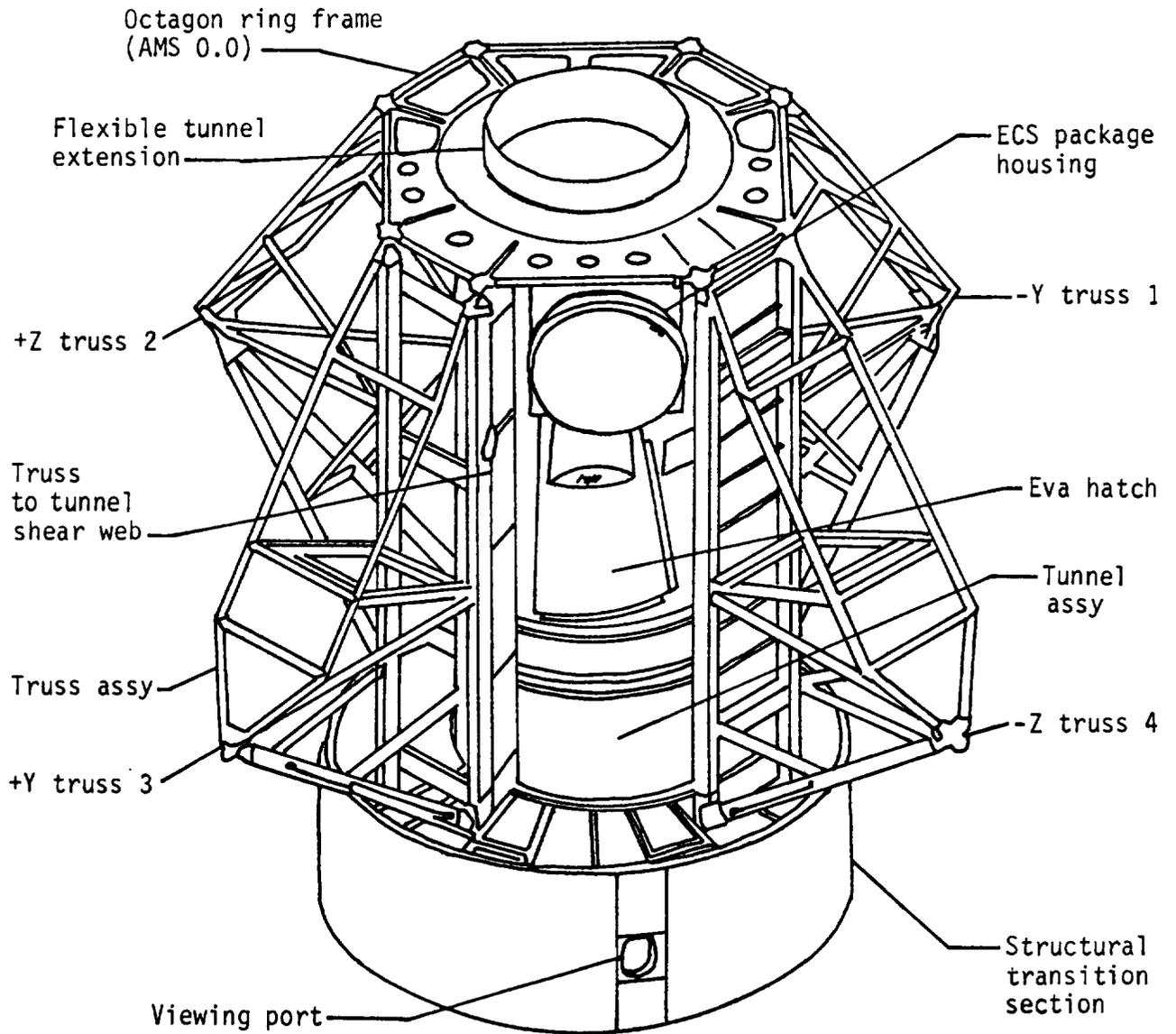


Figure II.E-8 Airlock Module

A stress analysis was performed on major structure using finite element computer techniques. The results showed the AM structure adequate in all areas except for a local section of the trusses. Subsequent component testing verified that the structure would not fail under the design loads.

The AM/STS was verified by proof and leak pressure testing of the mated sections to 8.7 psig. Later, when the AM was mated to the MDA, two leak tests were performed.

k. Fixed Airlock Shroud (FAS). This structure provided support and transferred load to the Instrumentation Unit (IU) for the PS, DA, AM, Oxygen (O₂) Bottles, four antennae, and EVA support equipment. The criteria were no test and factors of safety of 2.0 and 3.0 on ultimate. Analytical verification on primary structure resulted in overall positive margins of safety except for the outside supports of the O₂ bottles. Re-analysis showed the supports good for a smaller load factor than original design criteria, but still acceptable for flight (See paragraph II.E.2.j for vibro-acoustical testing).

The filament-wound O₂ bottles may be singled out for their size on a manned spacecraft. These six pressure vessels, approximately four feet in diameter by six feet in height, underwent extensive development and qualification testing programs. The two discone antennae extending 40 feet when deployed presented interesting features for zero-g simulation during testing.

1. Instrument Unit (IU). The functions of the IU were to provide mounting surfaces for electronic components, and transfer the load between the FAS and the OWS. The Skylab IU was identical to the Saturn except for relocation of some of the internal equipment. The Saturn testing was accepted as verification of the structural capability of the unit. Extensive analysis verified the local effects of equipment mounting and somewhat different environments. The vibro-acoustical test of the PA caused 23 components to be retested. Two additional small-scale static tests were performed to add confidence in the design.

Some of the major structural changes that the unit went through from its Saturn configuration were:

- (1) The insulation was changed to baked cork; and
- (2) Bonded doublers were added to the OWS interface.

The lower factor of safety plus ATM contamination requirements forced the insulation redesign and a foil cover was added to the insulation. The higher Skylab tension loads introduced the bonded doublers and testing was required to verify the integrity of the bond. Other major studies for this unit because of the long duration of the mission and the change in environments, included a micrometeoroid assessment,

thermal analysis of the effects of temperature on material degradation, and sealing of coolants for the thermo conditioning panels. None of the above had any major repercussions on the design.

m. Orbital Workshop (OWS). This module was a S-IVB stage converted into the primary living quarters for the crew (See Figure II.E-9). The OWS contained all the food, water, sleeping, eating, hygienic facilities, biomedical experiments, trash airlock, etc. Because the OWS was a modified S-IVB stage, many of the components were not requalified. All subassemblies were extensively re-analyzed with particular emphasis in the areas of new and modified structure.

Because of the many modifications, a complete vibro-acoustical test was performed on the entire assembly including the After Interstage. The objectives of this test were to verify acoustically-induced vibration design and test criteria, to demonstrate structural integrity of brackety and secondary structure, and to verify the analytical models used for dynamic load analyses. Acoustical and low frequency sinusoidal vibration tests were performed on the Dynamic Test Article (DTA). The DTA was a full scale, high-fidelity flight article simulation. The results of the test were the verification of the dynamic test criteria for OWS components for most cases, and revised criteria evolved for others. A summary of the work performed in each subassembly is given in the following paragraphs.

(1) Forward Skirt. Major additions to the forward skirt included the supports for the solar arrays and a thermal shield. Testing of the S-IVB/V forward skirt was accepted as qualifying for the OWS configuration. Extensive analysis was used to verify the integrity of the structure. The thermal shield was analyzed and a representative portion subjected to acoustical testing.

(2) Habitation Tank. Many alterations had to be implemented to convert the S-IVB propellant tank to the crew habitation and experiment station. The most significant alterations were the penetrations on the cylinder tank wall for the two Scientific Airlocks (SALs), the wardroom window, the access panel, the mounting of equipment through two floors, and the support structure for the water containers. Other packages were mounted directly to the tank. All these modifications to the original structure prompted dynamic and static load testing of a production type test article. The structure was also verified by extensive analysis.

The Static Test Article (STA) was subject to seven cases of combined loading including ground winds with the access panel removed and critical launch conditions. The purpose of these tests was to verify the structural integrity of the cylindrical portion and to determine the effects of rigging the meteoroid shield. As a result of the test it was determined that no general instability or local buckling occurred and no damage or permanent deformation was observed.

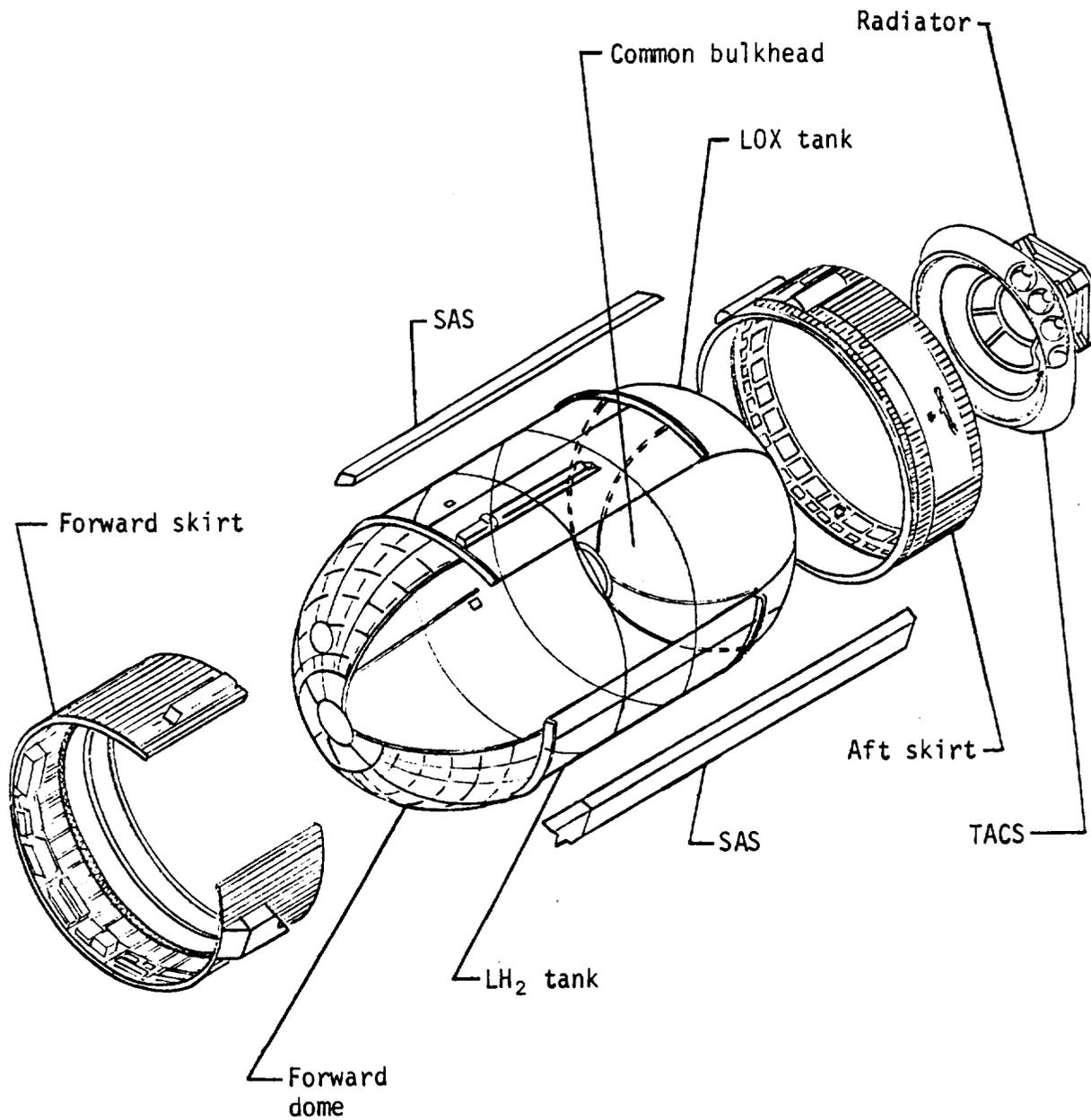


Figure II.E-9 Orbital Workshop Major Structures Breakdown

After the tests, the STA was subjected to an internal pressure of 32 psig. The objective was to demonstrate the structural integrity of the habitation area tank cylinder penetrations and the common bulkhead trash airlock penetration, and to demonstrate that there was no detrimental yielding or other damage. The test demonstrated all the objectives except for the failure of a butterfly hinge in the meteoroid shield. A redesign of the hinge was completed after the test.

Some of the interesting design innovations on the habitation tank are described here:

The entry hatch and its pressure equalization system presented a requirement of designing a handle that could not open before the pressure was equalized on both sides of the hatch. It also had to open rapidly once equalization was achieved, and be under control to prevent damage to the dome in the open position.

Of particular interest was the distribution of equipment in the crew quarters. Many studies were performed on how to arrange the masses without exceeding the capability of individual tank wall fasteners and how to obtain a uniform weight distribution in the periphery of the two floors. The floor grid configuration was adaptable to different equipment restraints and at the same time provided an astronaut foot restraint pattern. The design was accomplished with minimum weight expenditure, in spite of no test design criteria being available. The conical support structure used for both floors and water containers had to be designed to take fore-aft loads while allowing the cylinder tank wall to expand due to pressure. The joint with the tank wall was made flexible to bend as a hinge while the cone wall had to carry compression loads without buckling.

Another major design feature was the reinforcement of the tank wall at the penetrations of the windows and access door. This was accomplished with a minimum loss of tank buckling load-carrying capability.

Finally, the trash airlock presented an interesting linkage system allowing the ejection of disposables without impairing the seal.

(3) Aft Skirt. The aft skirt was qualified during the Saturn program. Major changes were the tie-down supports for the solar arrays and supports for the TACS structure. These modifications did not degrade the structural capability of the aft skirt and therefore retesting was not deemed necessary. Extensive analysis verified the integrity of the structure.

(4) Aft Structure. This was the S-IVB thrust structure which was modified to accommodate the TACS nitrogen gas storage spheres and the refrigeration system radiator. The aft and intermediate frames were both changed to provide the capability of carrying the new loads. Only vibration testing was performed on the new structure. Factors of 2.0 and 3.0 were used for static load in the analysis of the structure.

(5) Aft Interstage. The OWS Aft Interstage was almost identical to the S-IVB with only minor modifications. Therefore, the structural integrity was established primarily by comparing the loading environment of the OWS to that of the S-IVB, and to the structural capability determined from the S-IVB/V qualification and development tests.

(6) Solar Arrays. Extensive testing and analysis was used to verify the design compliance of the structure. Static test was performed on the beam fairing, the beam fairing hinge, and the wing stabilizer beam-to-beam fairing hinge assembly. Both launch and orbital loads were applied to the test articles. Vibro-acoustical testing was applied using 70-1 criteria (paragraph II.E.1.a.(3)). This criteria was too low in some areas and retest was required. As results of the tests, some parts failed, which required a redesign. Retest and a new math model were required before the unit was qualified for flight. The design of this unit is high lighted by the compactness of the solar arrays in the stowed configuration and the efficient functioning of the controlled rate of deployment.

3. Design Verification. Dynamics and stress analyses were performed in the following areas: Vibration Analyses, Loads Analyses, Acoustical Analyses, Dynamic Test Instrumentation/Plans, Mission Support-Contingency, Stress Analysis, and Studies.

Principally, the dynamics effort consisted of generating math models and subsequent updates of these analytical models due to design changes, structural module redefinition, impact of test data, and sophistication of models. The following paragraphs describe the effort on the DWS program.

a. Vibration Analyses. Vibration analyses were performed on numerous Skylab configurations, both baseline and contingency. Principal Skylab configurations analyzed were:

- (1) Baseline - Primary Effort
 - Launch configurations
 - Deployed orbital configurations
 - CSM docked to orbital configurations
- (2) Baseline - Secondary Effort
 - Orbital configuration with arrays stowed
 - Orbital configuration with ATM arrays deployed
 - Orbital configuration, ATM not deployed
- (3) Baseline - Contingency
 - CSM docked to axial and radial MDA ports
 - CSM docked only to radial MDA port

(4) Analyses Updates. Analyses updates were completed and modal property data generated in support of loads and control

studies. As analyses were generated during design and test phases, numerous analyses updates were accomplished. The principal updates were associated with:

- DWS Change from WWS Aug. 1969
- Sophistication of ATM DA and primary support structure Mar. 1970
- Sophistication of structural model includes backup structure Aug. 1970
- MDA port revisions incorporate influence coefficient test and updated models of arrays and FAS July 1971
- Incorporate math model changes due to Modal Survey Test results, ATM GRA sophistication, and revisions to OWS array due to Dynamic Test results Aug. 1972
- Final model that increased sophistication in GRA area, MDA port, DA and OWS arrays. Necessary due to control and load concerns. Mar. 1973

Of principal note was the development of large degree-of-freedom math models to accommodate sophistication and modal fidelity required in both load and control studies. A modal selection technique was developed to retain important structural modal properties with models of a size that could be handled.

b. Loads Analyses. Dynamic loads were derived on the modal property configurations, primarily for:

- Launch and boost conditions associated with payload responses and loads,
- Docking and latching loads for orbital mating with the Skylab WS,
- Deployment loads associated with appendages of the Skylab WS.

Principal load cycles or analysis updates were completed when revised modal data were available. Of principal note was the development and derivation of a docking and latching analytical program that represented a state-of-the-art advancement and a sophisticated boost phase loads program using a base motion approach.

The principal milestones associated with the loads analyses were:

- Latching load impact to MDA ports,
- Latching and boost phase load impact to the ATM canister,
- MDA port redesign to accommodate higher bending moment,
- Engine firing sequence change from 4-0 to 2-2 to alleviate ATM canister response.

c. Acoustical Analyses. Studies were completed to assess the transmissibility of noise through the structure; to refine design acoustical, shock, and vibration levels, and to update the design criteria where necessary. This included the correlation, evaluation, and subsequent criteria level updates due to analysis and dynamic tests.

d. Dynamic Test Instrumentation/Plans. The vibro-acoustical tests (both acoustical and modal survey) represented a "first" for overall size, structural complexity, and dynamic property refinement. The principal activities of the associated studies were the predictions of pretest analytical results for both launch and orbital configurations of the Skylab payload; the definition of instrumentation requirements which included the data retrieval-requirements, and the generation of an overall dynamics test plan.

e. Mission Support-Contingency. The dynamics activity associated with mission support involved four primary activities as follows:

- Analysis of the anomaly Skylab configuration to provide modal property data for, (1) Skylab control sensitivity studies, (2) Load impact studies, and (3) Redesign requirements.
- Analysis of on-going events, as docking/latching capability, parasol design, and MDA Six-Pack Rate Gyro design.
- Calculation of de-orbit loads and participation of SL-1 anomaly evaluation.
- Mission evaluation.

f. Stress Analyses and Studies. Stress analyses and studies were performed as described in the following paragraphs:

(1) Skylab A Strength Summary.

- Summarized structural integrity of major subassemblies using contractor stress reports where possible and doing additional analyses as required (including FAS, ATM, DA, and AM),
- Calculated and summarized loads at critical interfaces on cluster,
- Developed capabilities of all critical components and interfaces for updated load impact and mission evaluation, and
- Reviewed critical areas to ascertain flight readiness of each module.

(a) MDA Docking Port Influence Coefficients. Developed detailed computer models of MDA and monitored influence coefficient tests of MDA. Analytical finite element models were developed for the axial and radial docking ports. Static tests were performed to verify the models.

(b) ATM Alignment Modeling. Determined effects of spar alignment at one-g and use in zero-g environment and effects of temperature differentials on alignment.

(c) Stress Analysis Static Test Monitoring and Evaluation of AM/MDA. Predicted static test results and monitored static tests of AM/MDA. The AM/MDA was subjected to pressure and flight load tests with analytical models to verify and predict test results.

(d) Stress Analysis Static Test Monitoring and Evaluation of ATM. Predicted static test results and monitored static tests of ATM subassemblies.

(e) General Instability Analysis. Performed a general instability analysis on outside shell payload cluster. The objective of this task was to determine the loads at which general instability occurs during three phases of the launch environment, i.e., lift-off, maximum airload, and booster burn-out. An analysis of nonlinear collapse behavior in a critical region, and the determination of the actual factor of safety for PS and FAS (designed to higher factors of safety than the rest of the structure) were included.

The modeling of the Skylab structure was made in significant detail, which included discrete rings and stringers and other geometric and loading discontinuities. To limit the size of the problem, only a 180-degree segment of the structure was used. Even so, the analysis involved the solution of Eigenvalue problems with some 20,000 degrees of freedom that, perhaps, is the largest bifurcation buckling problem ever solved.

Results of this analysis showed that buckling occurred first at the OWS, which is the aft most section of the structure. The upper parts appeared to be well designed from the point of view of diffusing point loads into the lower parts of the structure. In general, the analysis proved that the structure had adequate factors of safety for all modules.

f. ATM CMG Study and Test Program. Analyzed, monitored, and interpreted the CMG test program. Two tests were performed, i.e., a CMG Rack Static Test and a Bench Test. A finite element computer model provided seventeen deflection cases for the Bench Test. The Rack Static Test was intended to detect structural deformations that would cause bindings in the CMG's operation. The results of both tests showed that the CMG operation would not be impaired by the load conditions imposed.

g. Finite Element Models. All models used in the dynamic tasks described in sections II.E.3.a through II.E.3.e herein, were constructed by stress. The final assembly represented the largest number of degrees-of-freedom used to that date.

4. Conclusions and Recommendations. In general, as it was evidenced by the successful completion of the four Skylab missions, all the structural and mechanical systems functioned properly and fulfilled their intended goals.

An exception was the OWS meteoroid shield that failed during SL-1 lift-off. Some other failures of minor consequences were encountered during the length of the mission. Nevertheless, the primary objectives of Skylab were adequately met and in many cases surpassed by the alertness of the crew members with the able support of the ground personnel.

Some pertinent recommendations for future programs are:

a. Design criteria documents binding all subcontractors should be initiated at the start of the program;

b. Timely coordination for interchange of data (particularly computer outputs such as stiffness models) is essential to avoid misruns and save time;

c. SOCAR reviews were successful tools for reviewing designs, and should be encouraged for future programs;

d. More capability for inflight maintenance and repair should be provided in manned space vehicles. Particularly, automatic devices should be provided for backup manual operation in case of malfunctions;

e. Assign a responsible project engineer for each major substructure. The duties of this project engineer should be the coordination of all aspects of analyses, design, fabrication, test, and assembly. This engineer should be free of administrative and managerial duties so he may devote most of his time to the technical aspects of the problem.

f. Place strain gages and accelerometers on critical structural items so data would be available for diagnosis of any malfunctions.

F. Electrical Power Systems

The Skylab Electrical Power System (EPS) configuration consisted of two independent and complementary power generating, storing, controlling, distributing, and monitoring systems. The Skylab Cluster used the available power to operate, control, and monitor the life-support, housekeeping, experiment, instrumentation and communication, and attitude control systems. All electrical power for Skylab was generated directly from the sun by photovoltaic solar arrays. Ni-Cd batteries stored the energy to allow continuous powering of loads during each orbital night. Power distribution and control was by means of a two-wire electrical network, which used a single point grounding system for the entire Cluster. The two independent power systems were designed to be operated normally in a parallel mode, thus permitting power sharing in either direction.

The complexity of the EPS imposed the development and use of analytical tools that could rapidly reflect the system configuration as it changed and yield accurate performance predictions. These tools included Load Assumptions and Power Allocation Documents and Computer Programs for System Analyses. Contingency analyses performed before launch included the possible failure of OWS Solar Array Wings deployment and thus proved invaluable for quick response to the real-time occurrence.

Pre-mission predictions for EPS performance required up-dating due to the reduction in AM EPS capability caused by the loss of one OWS Solar Array wing at launch and accelerated ATM EPS battery degradation. Several off-normal vehicle attitude maneuvers, which were imposed for vehicle thermal control until a sun-shield could be manually deployed, severely stressed the ATM EPS hardware. Restricted by debris from the meteoroid shield, OWS Wing 1 deployment was not possible, thus power scheduled for loads and for AM battery charging was not available. This condition presented an abnormal storage mode for the AM EPS until the crew of SL-2 cleared the restricting debris and deployed the solar array wing. The paralleling of the two power systems provided the necessary EPS flexibility, under a variety of nonscheduled and anomalous operating conditions, and with systems having differing degradation rates, to satisfy all imposed electrical loads and for supporting all maneuvers and operating conditions.

Pre-mission design verification was conducted at the component, black box, subsystem, system, and flight vehicle levels. Results from this program required some design modifications, performance requirements and prediction up-dating, and insight into hardware/system anomalies to be expected inflight as well as the knowledge of how to overcome, workaround, or repair those conditions. During the mission, unexpected anomalies imposed additional ground testing, using backup hardware and/or the Skylab Cluster Power Simulator (SCPS), to verify procedures before implementation by the flight crew.

Analyses of the data retrieved resulted in gaining significant and valuable EPS engineering knowledge, which was usable for establishing

effective design concepts and requirements for future spacecraft. Although the report is presented in discipline language and is primarily intended for discipline use, the information contained may be useful to designers to whom inter-system effects are important.

1. Design Requirements. The design requirements for the Skylab EPS evolved as the Cluster configuration changed from the original program design to the final hardware configuration. Cluster configuration development is discussed in detail in paragraph II.C.1. The original configuration involved two completely independent power systems; an AM/OWS Power System consisting only of primary batteries, and an ATM EPS consisting of a solar array, batteries, and power conditioning equipment. However, an even prior configuration was visualized as a parasitic type to receive its power from the CSM fuel cells.

a. ATM System. The ATM EPS did not change significantly from the original system (i.e., the solar array/battery type). The design evolution involved the number of Charger/Battery/Regulator Modules (CBRM), the solar array configuration, battery design, and mission duration and type. The mission concept began with the ATM as a free flying vehicle docking with the Skylab during the final manned mission. This involved the use of the LEM as a part of the ATM to provide electrical power before solar array deployment and propulsion before docking with the Skylab. At this time, it was planned to fly the Cluster in a Gravity Gradient (GG) attitude with the vehicle X-axis along the local vertical until docking with the ATM. After the ATM docked, the attitude was to be solar inertial. Z-LV attitudes were originally contemplated.

After the decision to change from a wet to dry workshop concept, the ATM became hard-mounted to the Skylab Cluster with preinstalled cabling rather than tethered umbilical cabling. The solar arrays were modified slightly in that the turnaround buses were bonded to the substrate for increased reliability. The LEM was deleted from the vehicle and the C&D Console was moved in the MDA.

During thermal vacuum testing, a problem was found in the ATM battery cell shorting to the battery case. The problem was resolved by the addition of fuses in the battery negative leads to prevent the possibility of a single short affecting the remainder of the CBRMs, and the redesign of the third electrode to provide uniform pressure over the entire cell area. A fourth electrode was added to improve the response of the third electrode signal, and also to assure the rapid and complete recombination of oxygen and hydrogen, which is normally produced. The other design change was the 20 percent increase of precharged cadmium plate surface area in each cell. The purpose of precharge was to maintain the useful battery capacity for longer periods of cyclical operation.

During post-manufacturing checkout, another problem occurred with the CBRM plus or minus 15 Vdc internal power supply transistors. The problem was resolved with the replacement of suspected components with transistors and diodes of higher rating.

Several failures were encountered with shorting of the wet slug tantalum capacitors in the input filters. The wet slug capacitors were replaced with tantalum foil capacitors. Following this modification of the input filter, a thermal vacuum and random vibration acceptance test was successfully conducted on the 18 flight CBRMs.

b. AM/OWS System. The Airlock EPS design evolved from a simple primary battery system to a complex solar array/secondary battery system. The evolution was prompted by changes in mission objectives and design requirements.

Until 1967, all system power after docking was to be derived from the CSM EPS. The AM EPS was required to provide only a minimal amount of power during the initial (predocking) mission phase, a period of only 11.5 hours. The AM EPS consisted of silver-zinc primary batteries and a power distribution system.

The mission duration was extended and the sophistication of the OWS increased to accommodate the growing experiment program. The AM EPS design concept was then changed to a solar array/secondary battery system with silver-zinc primary batteries to be used for pre-activation power only. The first of many concepts had solar arrays mounted on the AM. Through the evolutionary design phase, as the power requirements increased, the solar arrays were relocated on the OWS to accommodate the increasing array size. Also, in these early design stages, batteries and power conditioning equipment concepts evolved through a series of trade-off studies. One such study compared both silver-cadmium and nickel-cadmium batteries. The selection of nickel-cadmium was based on the availability of more ground test data and flight history implying less development risk. Several solar array/secondary battery system designs were evaluated, with the primary goal of increasing the overall efficiency and reliability of the system. Buck regulation was selected to maximize efficiency, for both the battery charger and voltage regulator. In addition, a peak power tracker was incorporated in the charger to extract maximum array power when demanded by the system. When the results of this design approach were established, the AM EPS consisted of four power conditioning groups (PCGs). Each group included a battery charger, a voltage regulator, and a thirty cell, 33-ampere hour, nickel-cadmium battery. Input power for the PCGs was derived from solar arrays mounted on the OWS.

Power requirements continued to increase thus requiring both a larger solar array and the expansion of the number of AM PCGs from six to eight. Reduction of preactivation load requirements, coupled with the increased available nickel-cadmium battery energy from the additional two units, led to the elimination of AM primary silver-zinc batteries.

At this time, the use of ATM solar modules, for both the ATM and OWS solar arrays, was considered important to achieve design standardization. Shortly after this, the "dry launch" concept was adopted,

which made the ATM an integral part of the cluster and made the OWS S-IVB a true space laboratory rather than a propulsive stage. Because the ATM attitude system was capable of holding the cluster in the solar inertial attitude at all times, there was no longer any need for a separate OWS solar array orientation system and the array articulation requirement was deleted.

A solar array was later conceived for the OWS that was to be used specifically with the AM PCGs as an integrated power system. Maximum and minimum voltage and power requirements were deliberately specified to be 1.5 times the ATM module design to minimize the impact on PCG redesign.

In the process of design evolution, a second ampere-hour (A-h) meter was added to the battery charger to improve reliability. Also a discharge limit feature was added to provide a signal to the voltage regulator when the A-h meter computed battery state-of-charge (SOC) equaled 30 percent; the voltage regulator then reduced its output and effectively removed the associated battery from the bus. This feature was added to prevent inadvertent overloading of any one battery, although intentional deep discharges were still possible by the use of override logic circuitry. Both onboard display and ground TM of the A-h meter status were available. Manual override of the 100 percent SOC signal from the A-h meter was added to permit continued battery charging in the voltage limit mode.

Battery cell failures during cyclical ground testing prompted a redesign of the battery case to aluminum for improved heat transfer to the coldplate. Internal cell changes were incorporated to reduce the probability of cell internal shorts. To further reduce battery operating temperature and therefore improve cyclical life, the coolant loop temperatures were lowered and both the A-h meter return factor and battery trickle charge rate were reduced. The latter necessitated battery charger design changes.

The conversion from a wet to dry workshop resulted in a complete redesign of the wet Power Distribution and Control Console. All the subsystem components could now be hard-mounted in the OWS before launch.

A console was developed within which the system electronic modules, circuit breaker panels, and control and display panels would be installed; however, the wet to dry conversion resulted in more systems and more sophistication. The circuit breakers, switches, and display arrangement was finalized in mid-1971.

In addition to the console-mounted panels, four "remote" C&D panels were baselined. The remote panels provided for crew control locally of functions that would be cycled many times during the mission. By providing the controls in the area of use, traffic to and from the power distribution and control console was considerably reduced.

c. Cluster EPS. Before the dry workshop concept, the ATM and AM/OWS EPSs were baselined as completely independent systems, each supplying its own loads. However, due to the Cluster load distribution, the available power margin on the ATM EPS was found to be considerably larger than that of the AM EPS. To provide a more flexible Cluster power system, and to provide better interface voltage regulation at the CSM interface, the normal operating procedures were revised to operate the AM and the ATM power systems in parallel. The power sharing was determined by the AM Regulated Bus Open Circuit Voltage (OCV) setting and the Cluster load distribution. The Cluster single-point-ground (SPG) concept was adopted. The ground point was in the AM when the CSM to MDA power transfer connectors were not connected, and in the CSM at all other times.

d. Final Design Requirements. The Cluster design requirements are completely described in the CRS. The major requirements from the CRS are included below.

(1) General Cluster Requirements. The SWS Electrical system as shown in Figure II.F-1 was comprised of two solar array/battery dc power systems; one located on the ATM and the other on the AM/OWS. The ATM and AM/OWS distribution systems were operated in parallel electrically. The SWS Electrical System was to have the capability of supplying 7530 watts of power to the Cluster loads while in the Solar Inertial mode. The system was to have the capability of supplying 6000 watts during the Z-LV Earth Resources Pointing Mode and 2600 watts during the Z-LV Rendezvous mode.

(2) AM/OWS System. The solar cell array mounted on the OWS and rechargeable batteries and associated power conditioning equipment located on the AM were to be capable of supplying 3814 watts of power to the cluster loads during the SI mode of operation, 3000 watts during the Z-LV-E mode of operation, and 1300 watts during the Z-LV-R mode of operation.

(3) ATM System. The solar cell array mounted on the ATM, and rechargeable batteries and associated power conditioning equipment located on the ATM were to be capable of supplying 3716 watts of power to the cluster loads during the solar inertial mode of operation, 3000 watts during the Z-LV-E mode of operation, and 1300 watts during the Z-LV-R mode of operation.

(4) Cluster Loads. Total Cluster loads were not to exceed 9000 watts steady state for limited time duration, and were not to exceed 7530 watts average per orbit with average day loads equal to average night loads.

- Of the 9000 watts, the load on the AM EPS at any time was not to exceed 5800 watts; 2900 watts per Regulator Bus.

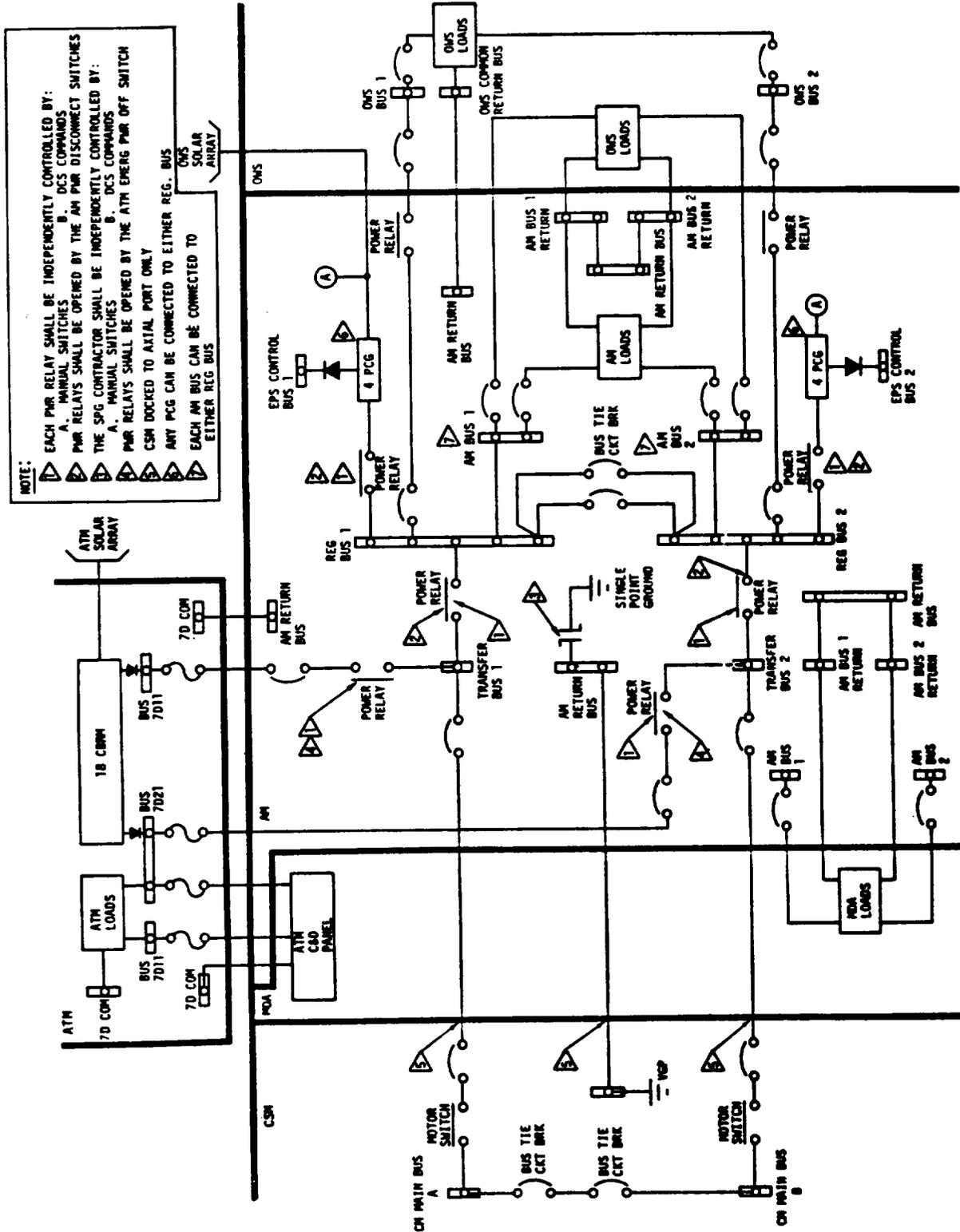


Figure II.F-1 Simplified Cluster Electric Schematic

- Of the 9000 watts, the load on the ATM EPS at any time was not to exceed 4800 watts; 2400 watts per bus.
- The minimum load on the AM EPS at any time was not to be less than 1920 watts; 960 watts per Regulator Bus.
- Energy balance condition was not to be exceeded by each of the 26 power subsystems during the SI mode. A minimum reserve capacity of 30 percent of rated capacity shall be maintained in each battery.

(5) Rechargeable Batteries. The allowable discharge levels of both ATM and AM Ni-Cd batteries was not to exceed the values specified under the following conditions:

<u>CLUSTER ORIENTATION</u>	<u>MAXIMUM ALLOWABLE DISCHARGE</u>
SI	30 percent Depth-of-Discharge (DOD) per Battery per Orbit
Z-LV	50 percent DOD per Battery during Z-LV pass, provided 30 percent of the Rated Capacity remained in the Battery

2. Functional Description

a. Major Elements. The Skylab EPS consisted of the following ATM and AM/OWS EPSs. The power systems are described both in the launch configuration and the configuration at launch of SL-4.

b. ATM Electrical Power System

(1) Launch Configuration Systems and Major Components. The major systems of the ATM EPS and their major components were as follows:

- Power Generation System (18 solar panels)
- Power Conditioning and Energy Storage System (18 CBRMs).
- Power Distribution System (12 distributors with redundant buses).
- Power Control System (switches, relays, logic circuits).
- Monitoring System (meters, indicator lights).
- Circuit Protection System (circuit breakers and fuses).

(a) Power Generation System. The 18 ATM solar panels converted sunlight into electrical power, which was processed by the Power Conditioning and Energy Storage System (the 18 CBRMs) and continuous power was provided to power subsystem loads through the Distribution System.

The ATM solar panels had a predicted combined power capability over the sunlit duration of about 10,480 watts at 55 degrees centigrade at the beginning of mission at zero beta angle. The 18 solar panels (one for each of the 18 CBRMs) were mounted on four wings. The wings were oriented 45 degrees to the longitudinal axis (X-axis) of the SWS. Figure II.F-2 shows the fully deployed array and depicts the numbering system adopted.

(b) Power Conditioning and Energy Storage System. Power conditioning and energy storage in the ATM EPS was accomplished by the 18 CBRMs and two load-sharing units (Primary and Secondary). Each of the 18 CBRMs consisted of a charger, a battery, a regulator and an Auxiliary Power Supply.

- Charger. The function of the charger was to charge its associated battery using power generated by its solar panel. The charger was of the nonisolated, step-down switching regulator type.
- Battery. Each CBRM contained an Ni-Cd battery rated at 20 ampere-hours. The battery contained 24 cells that were series connected, hermetically sealed, four-electrode type.
- Regulator. The function of the ATM buck-boost regulator was to regulate the voltage level of the power delivered by the CBRM to buses 7D10 and 7D20 and then to the ATM main buses 7D11 and 7D21 respectively.

The input power to the regulator was provided from the solar panel or from the battery or both. When the solar panel voltage was less than the battery voltage, all the input power was provided by the battery. The input voltage level could vary between 25.5 and 80 Vdc.

(2) Configuration at Launch of SL-4. The configuration of the ATM EPS at the time of launch of SL-4 was not radically different from that at launch of SL-1. The ATM solar arrays suffered from an average degradation of seven percent. Two CBRMs were inoperative due to solar array input contactor problems on CBRM 5 and a regulator failure on CBRM 3.

The results of the component degradation and failures resulted in a predicted SL-4 bus power capability for the ATM EPS of 3700 watts, beta angle = 0°, SI.

The CBRM batteries showed more degradation that was to be expected based on DOD and temperature effects. The average battery capacity available at the end of the SL-4 mission was 10.2 A-h with

Note:
 684 2X2 cm - or 228 2X6 cm SOLAR CELLS MAKE UP A MODULE
 20 MODULES MAKE UP A PANEL (POWER SOURCE)
 5 PANELS MAKE UP A WING
 4 WINGS MAKE UP THE ARRAY
 THE NUMBER ON EACH PANEL INDICATES THE CBRM TO WHICH IT IS WIRED
 VIEWED FACING ACTIVE CELL SIDE

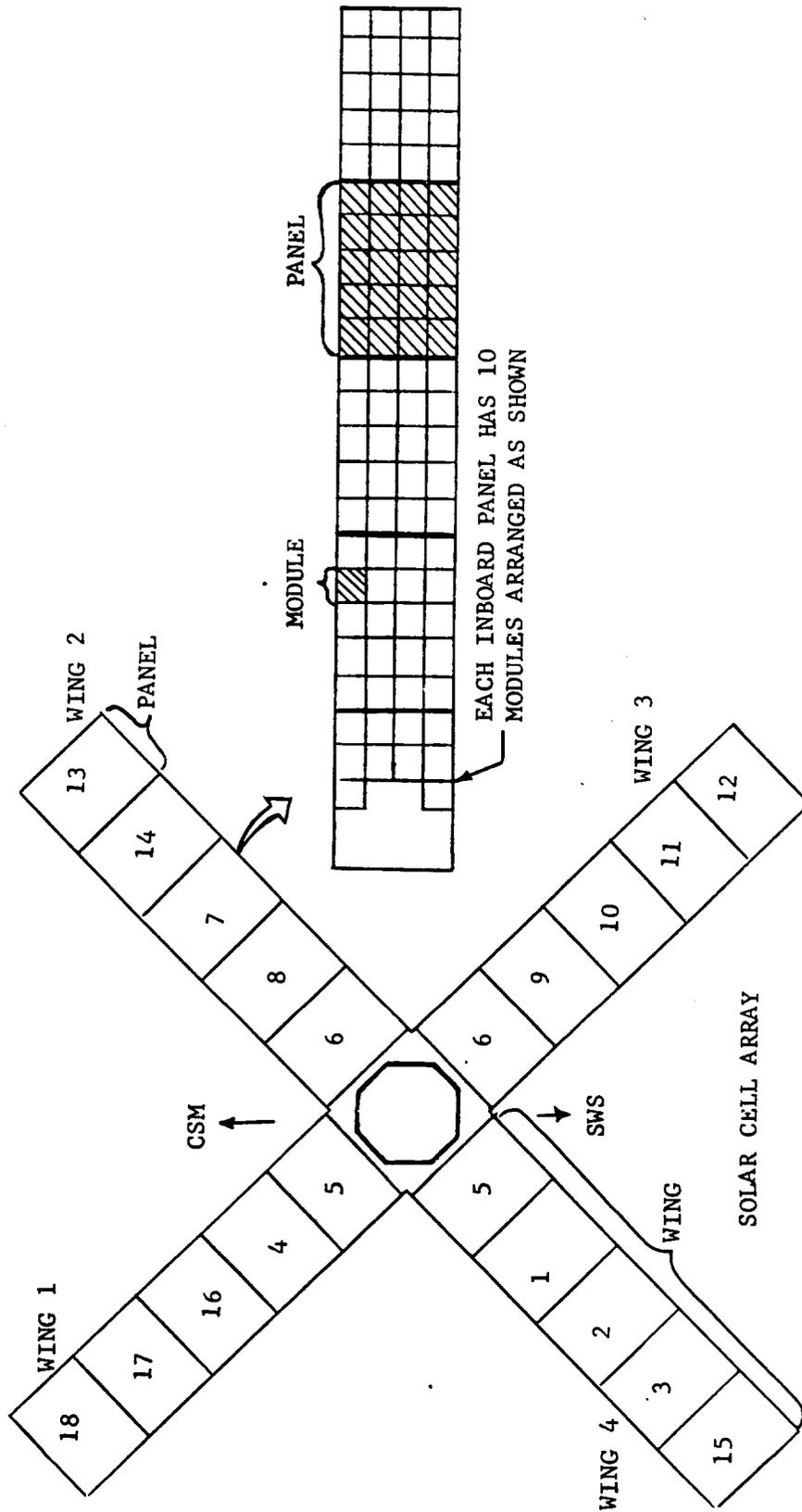


Figure II.F-2 ATM Solar Array Configuration

a standard deviation of 1.3 A-h. The cause of the increased degradation is thought to be long term trickle charging before launch.

c. AM/OWS Electrical Power System

(1) Launch Configuration Systems and Major Components.

The systems of the AM/OWS EPS and their major components were as follows:

- Power Generation System, 8 Solar Array Groups(SAGs)
- Power Conditioning and Energy Storage (8 PCGs)
- Power Distribution System (redundant buses)
- Power Control System (switches, relays, logic circuits)
- Monitoring System (meters, indicator lights)
- Circuit Protection System (circuit breakers and fuses).

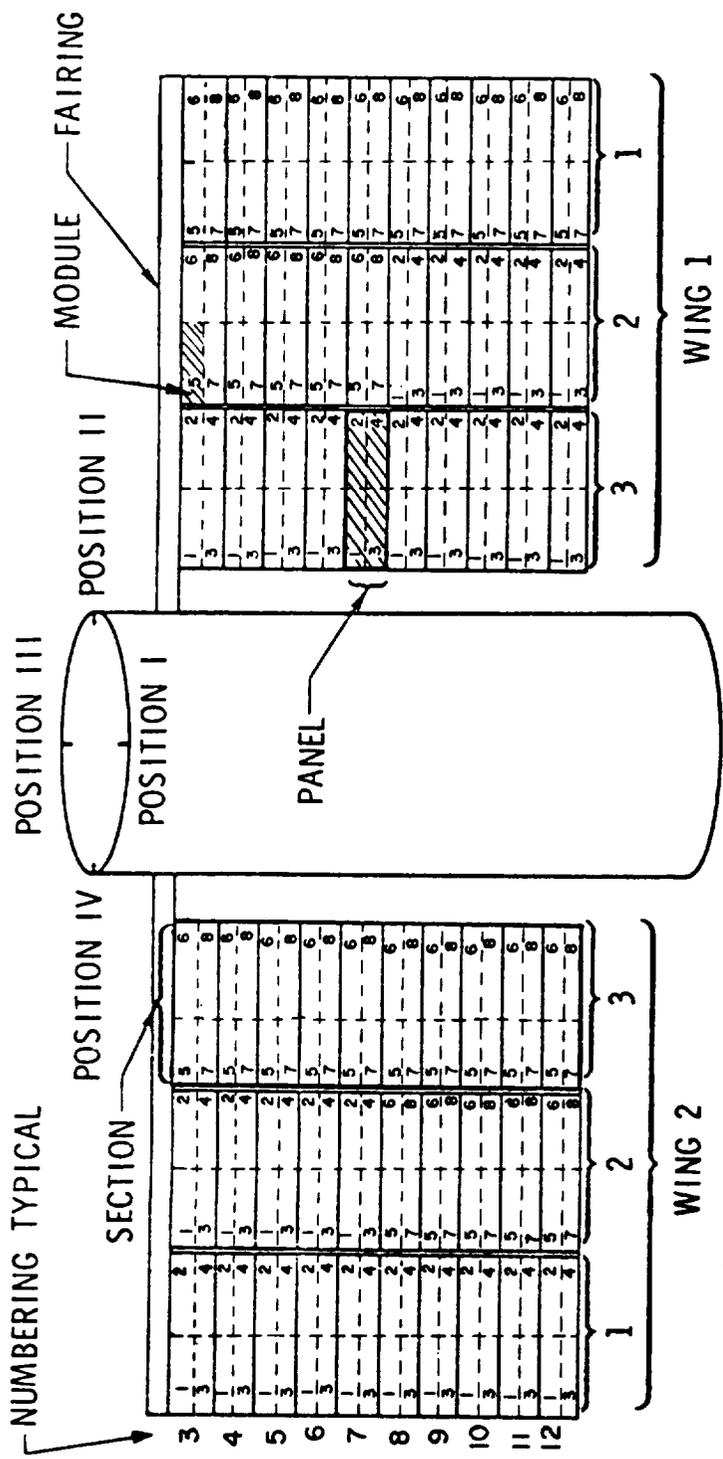
(a) Power Generation System. The generation of electrical power in the AM/OWS EPS was accomplished with the eight OWS SAGs. The SAGs converted sunlight into electrical power that was conditioned by the Power Conditioning System (PCS) and distributed to the subsystem loads and to the batteries for recharging. Each of the eight SAGs constituted an independent power source, one for each PCG. The SAGs were mounted on two wings as shown in Figure II.F-3.

(b) Power Conditioning and Energy Storage System-General. Power conditioning and energy storage in the AM/OWS was accomplished by eight PCGs and two Shunt Regulators. Each of the eight PCGs consisted of a battery, a charger, and a regulator. In addition, the PCGs contained sensing devices, controls, and interconnecting circuitry and were actively cooled.

Each PCG was designed to be capable of operating under the various levels of power provided by the SAG, to condition this power, recharge the battery, and distribute the power to the Skylab subsystems.

(c) Battery Charger. The battery charger consisted of a charger regulator, a peak power tracker, and an A-h integrator. The charger regulator contained a buck-type voltage regulator to provide a regulated and variable dc voltage to the battery and/or the bus voltage regulator.

- Battery. Each of the eight PCGs contained a 33 A-h Ni-Cd battery to store the solar array power and supply it to the bus voltage regulator when power available from the SAG was not sufficient to meet cluster load requirements.



Note:

- 616 SOLAR CELLS MADE UP A MODULE
- 4 MODULES MADE UP A PANEL
- 15 MODULES FROM WING 1 WERE CONNECTED IN PARALLEL TO MAKE UP AN ARRAY GROUP
- 10 PANELS MADE UP A WING SECTION
- 3 WING SECTIONS PLUS BEAM FAIRING MADE UP A WING
- WING 2 LOST PRIOR TO ORBITAL INSERTION
- THE NUMBER ON EACH MODULE DESIGNATES THE PCG TO WHICH IT WAS WIRED
- VIEWED FACING THE ACTIVE CELL SIDE

Figure II.F-3 OWS Solar Array Configuration

- Bus Voltage Regulator. Each of the eight PCGs contained a buck-type remote sensing regulator to provide regulated dc power to the AM Regulator buses and EPS control buses.
- Power Distribution System. Power distribution in the AM/OWS EPS was accomplished by a redundant system of main power buses and sub-buses distributing the power provided by the two independent groups of four PCGs each.

d. Configuration at Launch of SL-4. The major difference between the AM/OWS EPS at this time compared to that at SL-1 launch was the loss of OWS solar array wing 2. This resulted in a reduction in power capability of the AM/OWS EPS of approximately 40 percent. The system power capability at this time was 2900 watts, beta angle = 0° , SI. Time dependent degradation of the remaining solar array was not detectable. Battery capacity degradation was minimal, the average capacity being 33.6 A-h with a standard deviation of three A-h.

3. Interface Requirements. The EPS interface requirements are described in detail in the CRS. The most important requirement being the power transfer across interface. Power feeders having a maximum resistance of 15 milliohms per bus, were to be provided between the ATM interface and AM/OWS power distribution system and capable of carrying 2500 watts in either direction. Power feeders were to be provided between the SWS and CSM capable of carrying 2400 watts Interface voltages shall comply with Table II.F-1.

4. Design Verification

a. Analysis. Design verification analyses involved five categories: system or subsystem capability, power sharing, transient analysis, interface design limit verification, and load analysis. The analyses used both manual and computer tools. The following is a brief description of the major analyses performed.

(1) SWS EPS/CSM EPS Operation. The SWS EPS was required to provide power for the CSM quiescent mode and periodic systems checks after the CSM docked and was electrically mated. It was planned that the CSM fuel cells would continue to operate and provide all required CSM power until the cryogenics were depleted, approximately 12 days after docking. During this period the SWS EPS and the CSM EPS operated as completely independent power systems. During the initial umbilical mating verification, activation, and deactivation of power transfer and various CSM EPS verification periods, the SWS EPS operated briefly in parallel with either the fuel cells or CSM batteries. Numerous studies were performed to analyze the SWS EPS capability to supply the required CSM load and to analyze the SWS EPS/CSM EPS

Table II.F-1. Interface Voltage Requirements

INTERFACE		FUNCTION	MAX LOAD POWER (WATTS) See Note 6	STEADY STATE INTER- FACE VOLTAGE(VOLTS)	
FROM	TO			MIN	MAX
AM	MDA			MDA Loads	See Note 3
AM	MDA	Power from SWS to GSM (Via MDA)	2472	27.6	30.0
AM	OWS	OWS Buses	3000	25.5	30.0
AM	OWS	OWS Loads	See Note 3	25.5	30.0
MDA	GSM	Power from SWS to GSM (Via MDA)	2400	26.8	30.0
OWS	AM	Power from S/A Group to AM Power Cond.	See Note 4	51.0	125.0
ATM	EXP	Power Supplied from SWS to ATM Experiment(diode inside experiment)	See Note 3	26.0	30.5
ATM	EXP	Power Supplied from SWS to ATM Experiment(diode outside experiment)	See Note 3	25.0	30.5
ATM	AM	ATM C&D Power	382	27.8	30.5
AM	MDA	ATM C&D Power	382	27.3	30.5
ATM	AM	Power Transfer Between ATM and AM	2500	28.3	30.5
MDA AM OWS	EXP	Power Supplied from SWS SWS to Experiment	See Note 3	24.0	30.0

- NOTE 1. Maximum load power listed corresponds with minimum interface voltage.
2. Minimum load power is zero and corresponds with maximum interface voltage.
3. Each individual load must meet the minimum steady state interface voltage level at its individual steady state maximum load. See Module Power Allocation Documents for individual load requirement.
4. The minimum average power over the sunlight portion of the orbit supplied by the Solar Array Group at 51 volt operating point at the interface during the Solar Inertial Mode is 1312 watts.
5. The interface voltage requirements do not include signal and control power.
6. The maximum load given is shared equally between the two positive buses in the two bus system where applicable.

operating compatibility. The analyses showed that the SWS/CSM power system were compatible under the above conditions.

(2) Cluster Load Versus Capability Analysis. The SWS EPS power capability was affected by two major mission variables, Skylab orientation mode and time (beta-angle variation and degradation of both solar array and battery).

The major time dependent degradation factors were the battery capacity decay and the reduction in the available solar array power. The capacity decay rate was affected by the battery DOD per-orbit and temperature while a major portion of the solar array power degradation was attributed to the thermal cycling effects.

Conclusions that were drawn are:

- Solar inertial capability satisfied the load requirement in all mission phases.
- In certain Z-LV-E passes, the capability did not meet the worst-case load requirement. In these cases, load management was required to perform the Z-LV-E operation.

(3) Load Analysis. Detailed load analyses predictions were performed for the three missions for both the SI and Z-LV modes. It was shown that the predicted loads could vary widely within a given orbit.

The load analyses performed indicated that with proper power management the EPS had sufficient capability to supply the load required to meet planned program activities as scheduled in the premission flight plan.

(4) Grounding. Several studies were conducted to assess the Skylab grounding system for both the orbiting cluster and the ground checkout configurations. The most significant of these studies were:

- A study on EREP grounding in March 1971 resulted in a design change to the grounding configuration of the EREP system.
- An information report that summarized the grounding criteria on primary and secondary power systems used on Skylab was prepared in April 1971.
- In August 1971 an analysis was conducted on the AM suit compressor power inverter SPG fault current to determine the impact of this fault current on cluster system operation. The results were presented at the 16th Electrical Panel Meeting in October 1971. Analysis results indicated no significant system degradation would result.

- In October 1971 results of a review of the ground checkout configurations at KSC were presented at the 16th Electrical Panel Meeting. Conclusions were that the mating of the ESE umbilical connectors to the cluster and launch vehicle established numerous structural return paths which were in parallel with the return wiring for circuits using structural ground. The magnitude of the ground return currents was not detrimental to the operation and performance of Skylab.
- A detailed review, concluded in March 1972, of the as-built production drawings of Skylab hardware was conducted to identify grounding violations. All such violations were waived.

(5) Circuit Protection Versus Wire Compatibility. During SOCAR each module contractor reviewed the power distribution network to assure that each circuit protective device adequately protected the power distribution wiring.

It was concluded that with the hardware changes occurring during the SOCAR and with the completion of the activity requested to review internal wiring of experiment equipment, the circuit protection was compatible with the wiring and no further action was required.

(6) Corona. Each item (experiment/equipment) assigned to Skylab was analyzed for Corona susceptibility according to peak-applied operating voltages and operating products, residual and contaminating atmospheres both in and near the item being investigated. Those items having field stresses greater than 50 volts/mil were recommended for either qualification or special testing to evaluate the corona susceptibility.

(7) Contingency Analyses. Several detailed analyses were performed to evaluate possible contingency modes of operation. These contingency modes included: failure to deploy OWS and/or ATM solar arrays, failure to deploy meteoroid shield, and failure to deploy the ATM. These analyses resulted in remedial and alternate sequences to be adopted in the event of various subsystem or component failures.

b. Testing. Testing of the Skylab EPS was conducted at the component, black-box, subsystem, system, and flight vehicle levels. The objective of all test programs was to assure that the flight vehicle would meet all Skylab requirements with a high level of confidence. The overall testing can be divided into three categories: Development or Engineering Model Testing, Qualification and Acceptance Testing.

Essentially all major EPS components were subjected to developmental testing. These components include both AM and ATM batteries, chargers and voltage regulators. Qualification and acceptance testing was required on all individual components and functional units that

were to comprise the Skylab EPS. In addition, all systems were subjected to integrated testing at KSC.

The results of the component and subsystem testing are shown in Tables II.F-2 through II.F-5 below.

Table II.F-2. ATM Solar Array Performance*

PARAMETER	SPECIFIED OR PREDICTED VALUE	ACTUAL VALUE	SOURCE OF DATA
Module Specification Requirement	700 Milliamps at 49 Volts	Test Panel I Avg Value for 20 Mod	X-75 Simulator Test
		730.6 Milliamps at 49 Volts	
		726.3 Milliamps at 49 Volts	Denver Sunlight Test
		Test Panel II Avg Value for 20 Mod	X-75 Simulator Test
		797.2 Milliamps at 49 Volts	
		783.2 Milliamps at 49 Volts	
Power Output	Test Panel I 681.3 Watts Maximum	715.5 Watts Maximum	**
	Test Panel II 752.7 Watts Maximum	785.3 Watts	**

*All values at 30°C

**Predicted value using X-75 simulator output of individual modules; actual value based on sunlight test.

Table II.F-3. CBRM Performance

PARAMETER	SPECIFIED VALUE	ACTUAL VALUE	SOURCE OF DATA
Battery Cycle Life	4000 Cycles Operation	Curve based on test data	Battery cycle test
Charger Efficiency	> 92%	92.9 to 94.3	CBRM Electrical ATP
Regulator Efficiency	> 89% from 100 to 200W	90.5 to 94.1	CBRM Electrical ATP
	> 85% @ 400W	84.0 to 86.8	

Table II.F-3. (continued)

PARAMETER	SPECIFIED VALUE	ACTUAL VALUE	SOURCE OF DATA
Charger Control of Battery V versus T Characteristics	Specified curves ± 150 mV	Specified curves ± 100 mV	CBRM Electrical ATP
Maximum SA Current (Charger On)	13.5 ± 0.5 A	13.5 ± 0.1 A	CBRM/Solar PNL sunlight test
EMI Requirements	Meet 50M02408D	Out of Specification on conducted & Radiated interference	CBRM Qual test
Life	4000 Cycles	Verified	Life test
PARAMETER	PREDICTED VALUE	ACTUAL VALUE	SOURCE
Continuous Bus Power capability of 1 CBRM /SA Subsystem (Worst Case SA)	218 Watts @ the bus	227 Watts	CBRM Life testing with simulated solar array
Temperature Range of batteries under hot & cold predicted environments	-10°C to $+30^{\circ}\text{C}$	-10°C to $+30^{\circ}\text{C}$	ATM Prototype TV testing
Power mismatch between CBRMs-Controlled by power share circuits	5% for 100W to 300W per CBRM	3.5%	ATM Prototype TV testing

Table II.F-4. OWS Solar Array Performance

PARAMETER	SPECIFIED VALUE	ACTUAL VALUE	SOURCE OF DATA
Module Specification Requirement	944 Milliamps @ 71.7 Volts @ 28°C	970 Milliamps @ 71.7 Volts @ 28°C	Flashlamp test

Table II.F-5. PCG Performance

PARAMETER	SPECIFIED VALUE OR TEST PURPOSE	ACTUAL VALUE OF TEST RESULTS	SOURCE OF DATA
Battery Charger Life Test	1000 hour test	Within specified values	Life test
Battery Cycle Life	4000 Cycles	Verified	Life Test
Voltage Regulator Life Test	1000 hour test	Within specified values	Life Test
SAG/PCG Compatibility	Determine operating characteristics & compatibility	System compatibility was verified & operating characteristics were determined	Denver Sunlight test
PCG	Predicted Max SI Mode: 0° β 530 W 58.5° β 850 W 73.5° β 1500 W Predicted Max Z-LV Mode: 0° β 300 W 73.5° β 40 W	540-563 W 890-930 W 1354-1453 W 300-375 W 80-90 W	Battery Module tests
Capability of 4 PCGs	Predicted Max SI Mode: 0° β 2120 W Predicted Max Z-LV Mode: 0° β 1200 W	2150 W 1300 W	Battery Module tests
Peak Power Tracking Accur.	Predicted 95-100 %	95.4 to 99.48%	Battery Module tests
Regulator Droop Characteristics	0.04 ± .002 volts/amp	Verified	Battery Module tests

c. Skylab Cluster Power Simulator Testing (EPS Breadboard). The purpose of the EPS Breadboard was to provide a means to demonstrate the operation of the ATM EPS in parallel with the AM EPS, and to insure stable operation of the two power systems under various load conditions before mating of the actual flight systems. Other areas of investigation were proper load sharing between the two systems and an analysis of the single point ground system. Secondary objectives were to provide a means to demonstrate and analyze power system failure and contingency modes of flight operation as well as to provide an alternate means of simulating orbital performance (day-night cycle, Z-LV-E mode). The Breadboard was also intended to be used during the mission to analyze performance and to verify solutions to problems occurring during flight.

(1) System Description. The EPS Breadboard hardware consisted of both flight systems hardware and ESE hardware. The flight (or flight equivalent) hardware included 8 PCGs, 18 CBRMs, and ATM Power Transfer Distributor, AM power distribution system, and three AM control, display, and circuit breaker panels. The ESE equipment included: ATM solar array simulators, OWS solar array simulators, cluster load banks, a CSM source and load simulator, network control and switching equipment, a digital data acquisition system, a low temperature test unit, an air conditioning system, and various ESE C&D panels. All power distribution interconnecting cabling was made equivalent to flight wiring.

(2) Testing. Testing on the breadboard began in February 1972. Testing was performed in compliance with the "Skylab Cluster Power Systems Breadboard Test Requirements" document, 40M35693. The breadboard was also used as a training aid during classes on the Cluster EPS for flight control and astronaut personnel. The major tests performed are shown in Table II.F-6.

5. Sneak Circuit Analysis. The goal of the sneak circuit analysis was to uncover any condition that, due to a sneak electrical path (an undiscovered, unwanted electrical path), could cause unforeseen problems in the EPS. The Sneak Circuit Analysis performed on Skylab was effective for reasons other than equipment and personnel safety and mission success such as:

- Establishment and maintenance of a complete set of documentation.
- Verification of interfaces within and between modules.
- Development of simplified schematics used to conduct an evaluation of the activation circuitry, system sequence checks, and crew procedures.

The use of the computer as a tool in circuit analysis on programs as large as Skylab was unique; however, the technique proved itself to be both economical and essential in assuring that all electrical paths were identified. The performance of this type of task by manual methods would have been extremely difficult and inefficient considering the complexity of the Skylab EPS.

a. Analysis Description. The sneak circuit analysis performed included the following modules of Skylab: ATM, MDA, AM, and OWS. The ESE and the Skylab interfaces with the IU and CSM were included in the analysis. Those IU functions that controlled Skylab systems were analyzed. Experiments associated with the Skylab were also a part of the analysis. The CSM was analyzed separately by the Boeing Company (TBC), Sneak Circuit Analysis Group in Houston, Texas.

Table II.F-6. Tests Performed on Skylab EPS Breadboard
(Reference 40M35693)

<u>REF PARA</u>	<u>TEST PERFORMED</u>
6.7	CSM Power System Verification
7.3.1	Initial Paralleling Verification
7.4.3	Battery DOD Prediction Verification
7.3.3	SWS EPS/CSM Fuel Cell Parallel Operation
7.3.4	SWS EPS/CSM Descent Battery Parallel Operation
7.3.7.5	Bus Interface Voltage Limit Test
7.4.1	Switching Test
7.3.7.1	CSM Feeder Transient Test
7.3.7.2	CSM Feeder Noise Test
7.1.14	CSM/XFER Bus Noise Test
7.3.7.3	Power Sharing Test
7.4.2	Contingency Mode Testing
7.3.2	Z-LV-R Simulation
7.3.6	Solar Inertial Operation
7.3.8	Z-LV-E Operation

SPECIAL TESTS OR APPLICATIONS

AM Battery Testing (premission)
 Flight Crew Training
 Flight Controller Training
 SL-1/2 Battery Storage Test
 SL-3 AM EPS Shutdown Procedures Test
 SL-3 SAS 4 Current Anomaly Test
 AM Battery Recharge Procedure Test
 Coolant Loop/PCG Deactivation/Activation Procedure
 Voltage Regulator Thermal Checkout
 CSM Power Transfer Circuit Check
 ATM Battery Capacity Test
 CBRM 17 Low Output Analysis
 CBRM 3, 5 Interconnection Test

The analysis was limited to the time period from prelaunch to mission termination. The ESE umbilical power and control circuits were analyzed for the time period from just before initiating the automatic sequence until after umbilical separation. Circuitry of the airborne modules and interfaces defined previously were analyzed for the operational modes of each mission phase, including prelaunch, launch, orbit insertion, orbital operations associated with docking and undocking of CSMs, and OA operations through mission terminations.

The analysis included the primary power and control circuits, switched secondary power and control circuits, switched signal circuits, command circuits, and computer interface circuits. Certain non-switched signal circuits, the grounding trees and most of the digital logic circuitry were excluded. Electrical functional changes reflecting CCB action were included. Minor electrical changes made without CCB approval were also included in the analysis.

Analysts were initially trained in the techniques of data encoding and analysis. The analysts applied the topological diagrams and sneak clue techniques to each of the network trees to identify potential sneak circuit conditions.

b. Program Concept. The Sneak Circuit Analysis effort was worked on a team concept consisting of NASA, MMC, TBC, MDAC-ED and McDonnell Douglas-Western Division (MDAC-WD). The reason for the team concept was to expedite the overall analysis effort and to implement timely corrective action.

The NASA (MSFC) supported all phases of the analysis. The MMC prime function was to manage the team, obtain the data for the analysis, evaluate potential sneaks, and ensure implementation of corrective action. The TBC prime function was to analyze the Skylab circuitry and identify any potential problems. The MDAC-ED and MDAC-WD prime function was to assist MMC in the data area and support TBC in coordination with the design engineers for potential sneak circuits analysis or identification.

A review board, consisting of a member from each organization, was established to dispose of all reports.

c. Data Operation. The data collecting and filing activities, which were performed to support the Skylab Sneak Circuit Analysis, had as their prime objective the provision of accurate, complete, and current information for the analysis. Over 6,000 items of data were received. Of this total 4,000 were schematics or wire lists. The

balance consisted of integrated schematics, specifications, system handbooks, operating procedures, malfunction procedures, and other reference documents.

d. Data Acquisition. Data in both microfilm and hard copy forms were identified and received, which provided a description of the electrical circuitry and its operation. However, after microfilm was used for several months it was determined that it was not program effective to continue its use in all cases. Only those drawings that were used for analysis only, such as specification control drawings, vendor specifications, and procurement drawings continued to be used in the microfilm form. Timely receipt of this information was required for all of the circuitry within the scope of the analysis. These data included any type of information that accurately specified circuit continuities or aided in the understanding of the operation of the systems having electrical circuitry to be analyzed. Accuracy of the information obtained was assured to the extent possible by selecting wiring and schematic information from which the cables and equipment were to be manufactured. The data were checked wherever possible to assure that the true electrical configuration of Skylab was being used in the analysis activities. The data received for exclusive use in the sneak circuit analysis were retained in files.

Electrical schematics were the most important data received and used. Schematics at the integrated system level and the detailed "black box" level, which included "proprietary" information, were received and used.

e. Results. The task involved the acquisition, correlation, and encoding of over 4,000 detailed schematics and wiring lists for the various modules. These data represented the 2,800 black boxes (reference designators) in Skylab. The data input to the computer programs is shown in Table II.F-7.

Table II.F-7. Sneak Circuit Computer Input Summary

MODULE	BOX INTERNAL DATA (BID)	BOX EXTERNAL DATA (BED)	TOTAL WIRE SEGMENTS (RECORDS)
ATM	92K	22K	114K
MDA	22K	6K	28K
AM	46K	12K	58K
OWS	57K	14K	71K
TOTALS	217K	54K	271K *

*In addition, approximately 25,000 records in the ESE, portable equipment, experiments, and instrumentation areas were analyzed using manual analysis techniques.

As a point of reference the Skylab CSM consisted of 22,000 BID records and 13,000 BED records for a total of 35,000 records. Thus Skylab was approximately 7.8 to 8.5 times as complex as the Skylab CSM.

Eight new computer programs were developed and 17 programs were modified to provide assistance in performing and managing the analysis. The purpose of these programs varied from tracking of input documents and output reports to automatically drawing network trees from information in the data base. These programs significantly reduced the effort and cost of performing the analysis, provided a high degree of visibility of analysis and changes, and insured that every possible electrical path in the subsystems covered was considered. A total of 400 computer hours (IBM 260/65 and 370/155) was used in the analysis effort.

The computer runs resulted in the output of the following data for analysis:

<u>MODULES</u>	<u>NETWORK TREES</u>	<u>PATHS</u>
ATM/MDA	3,474	21,354
AM/OWS	<u>5,418</u>	<u>26,230</u>
TOTALS	9,892	47,584

A total of 1,530 change packages were received and analyzed. Of these 312 were electrical functional changes.

The analysis resulted in the preparation of 259 Sneak Circuit Reports. Many reports described more than one sneak circuit condition. A significant by-product of the analysis was the identification of drawing errors. Over 300 Drawing Error Reports were released.

The Sneak Circuit Reports were reviewed and disposed of. The disposition was as follows: 44 Sneak Circuit Bulletins; 40 Problem Reports; 91 Design Concern Reports, and 17 Drawing Error Reports. Corrective actions resulting from review of these reports included 20 hardware changes, 37 procedural changes, 4 documentation changes, and 5 test constraints. In addition over 45 hardware changes resulted from the Drawing Error Reports. All Sneak Circuit Reports were disposed of and closed out. Several Drawing Error Reports remained open because the original drawings were no longer maintained. However, notification of the errors was made to all concerned organizations involved in the test, mission control, and mission support areas.

6. Conclusions and Recommendations. Except for the loss of OWS Solar Array Wing 2 at the beginning of the SL-1 mission, the Skylab EPS performed as expected with minimal operational anomalies. The two power systems (ATM and AM/OWS) operated compatibly in parallel providing sufficient power capability for both SI and Z-LV operating modes. None of the anomalies or system degradations were of sufficient magnitude to cause the immediate loss of sufficient power to cancel critical activities or to cause the loss of any prime mission objective.

Specific recommendations for future missions include the use of solar cell interconnector materials that more closely match the solar cell material and where possible elimination of the solder interface. This will be necessary for missions imposing large quantities of temperature cycles. For optimum power transfer between the solar array and the power conditioning equipment include peak power tracking in future power control and conditioning designs. In addition future design should include sufficient instrumentation to permit effective engineering analyses of performance and anomalies.

Paralleling of the two power systems proved to be a good means of providing excellent EPS flexibility under various operating conditions and differing system degradation rates. The design feature was at least partly responsible for the long duration of the Skylab mission.

G. Communications and Instrumentation System

The SWS Instrumentation and Communications (I&C) System was the electronic equipment used to provide information and control between the Skylab orbiting vehicle and the ground, and between the crewmen in Skylab. The I&C System specifically provided audio and visual communications, subsystem and experiment status information, biomedical monitoring, command signals, and rendezvous ranging signals. The system was divided into seven major portions, as follows:

- OA Audio
- OA Television (TV)
- ATM Data
- AM Data
- ATM Command
- AM Command
- SWS/CSM Ranging

Each portion of the system had interfaces with other systems, namely, the CSM, the IU, Skylab Experiments, Launch Complex 39, and the Space Tracking and Data Network (STDN).

1. Design Requirements. The SWS Communications System design was established to meet the requirements of the following documents:

- Cluster Requirements Specification, RS003M00003
- Skylab Frequency Plan Instrumentation and Communications Interface, ICD 50M13120
- Skylab to MSFN Instrumentation and Communications Interface, ICD 50M13126
- Skylab Orbital Assembly Audio System Requirements, ICD 50M13136
- Skylab Orbital Assembly Television System Requirements, ICD 50M16132
- Module, Subsystem, and Intermodule Interface Control Documents

a. Intercenter Panel. Definition and resolution of all I&C interface problems were delegated to the I&C panel in March 1967 by the director of the Saturn AAP. The charter meeting of the panel was held in April 1967, and over the course of the total AAP and Skylab programs, 16 meetings were held. The task of the panel was significantly reduced in September 1968 when the LM and the AM were assigned to MSFC for program implementation. At this point a number of interfaces were either eliminated or reduced to level B (intracenter-intercontractor). During the program, subpanels and ad hoc working groups were formed with the panels sponsorship to work in specialized areas. Examples of these groups are the RF System Subpanel, the Electromagnetic Interference (EMI) Subpanel, the Data System Subpanel, the Audio Working Group, and Transducer Working Group.

b. Data Systems. Early configurations established a data system in support of the ATM and a second in the AM. These systems were baselined using existing equipment designs. The designs represented equipment from the Saturn program in the case of the ATM and the Gemini program in the case of the AM. As the program evolved system configuration changes occurred. Generally, the changes were directed to expanding capacity and insuring the achievement of the required operating life.

In the case of the ATM the addition of Remote Analog Submultiplexers (RASMs) provided additional measurement capacity and the development of the ASAP equipment provided for storage and recovery of selected data during the periods when RF contact was not available.

The Gemini system configuration was revised by the addition of the PCM interface box. The capability obtained by addition of this box included additional channels by dividing down some high sampling rate channels included in the original PCM format. This made available added portions (subframes) of the format for recording more than the single subframe that was recorded in Gemini, and provided a means of selecting between redundant programmers to insure system operating life. As part of the data system, multiple recorders were installed to insure reliability and record increased amounts of data when no ground station contact was available. Recorder modifications were made to permit recording of digital experiment data not identical to the Gemini format and to record voice on a second track.

c. Command Systems (Including RF Systems). The Command Systems, as did the data systems, used equipment developed for earlier programs, specifically Saturn-IU equipment on the ATM and Gemini on the AM. The systems incorporated redundancy as was normal for command systems.

The AM command system had a teleprinter added as an output. The unit operated from a standard format command signal having a separate system address. The equipment was unique to Skylab and was used daily to provide updated flight plans, menu changes, revised operating procedures, repair instructions, and a variety of other communications. During development, a challenging item was the selection of a writing medium that was the proper tradeoff between flammability and clarity of reproduction.

The baseline systems incorporated redundant transmitters on both the ATM and AM to assure availability during the life of the program. The ATM was baselined with 10 watt transmitters while the AM used the 2 watt Gemini transmitters. Analyses were conducted on the transmitter links and the marginal nature of the AM 2 watt units resulted in direction to switch to 10 watt transmitters. Another revision in the program resulted in a single 2 watt transmitter being incorporated in the communications system (redundant in frequency to one of the ten watt units) for use during boost and the early flight period. The

change was incorporated as a result of analyses that showed the partial pressure from outgassing and evaporative cooling systems in the IU, had for several hours after launch, the potential of causing arcing at the power and potential levels used in the 10 watt units.

Each antenna system for the ATM and AM involved ground selection for the best coverage for any ground station contact. Revisions were made in the switching matrix on both modules during program reviews to insure that a failure in switching systems would not prevent transmission from another antenna.

d. Ranging System. The ranging system was incorporated as an aid to the ascending CSM to conduct an efficient rendezvous with the orbiting SWS. The equipment on the SWS was identical to that carried on the LM ascent stage in the Apollo program. A high gain directional antenna was designed and installed on the SWS to maximize the distance at which ranging data would be available. The antenna was designed to produce a pattern fitted to the nominal approach path.

e. Audio System. The baseline audio system was a wire extension of the CSM audio panels to permit headsets to be plugged in throughout the modules of the SWS. Requirements reviews and systems analyses resulted in the establishment of stations where Speaker Intercom Assemblies (SIAs) were installed throughout the cluster. These SIAs were equipped with speakers and a push-to-talk microphone to permit communication between Skylab crewmen or between crewmen and the ground. Special EVA and IVA stations allowed suited crewmen to tie into the system. The SIAs also provided for control of an audio recorder, the pickup point for operational biomedical information, distribution of C&W alarm tones, and plug-in capability for communications via headsets.

f. TV System. Various proposals on the incorporation of a TV system in Skylab were presented starting late in 1967. No program direction was given to incorporate the system until October 1968. The initial system installed was based on real-time transmission only. Television images to be transmitted included general working scenes throughout the SWS using the Apollo color camera and pictures from the ATM scientific cameras.

System evaluation of possible use of TV brought about the design and development of a remote control lens to be used in conjunction with the SAL and boom system developed for Experiment T027. This combination of equipment would permit the extension of a camera outside the SWS for exterior views. The system was never used because one airlock was used for the umbrella shade and the boom mechanism had to be ejected from the other airlock due to a failure. Continued analysis of possible TV scenes and available ground contact time led, in 1971, to incorporation of a video recorder. Use of this recorder freed the crewmans use of TV in sending pictorial data from the times and periods of ground station contacts.

The final addition to the capability of the TV system was the addition of an adapter to permit the TV camera to pick up the image from the Viewfinder Tracking System (VTS) optics of the EREP equipment.

2. Functional Description. The total I&C system was used by the SWS when docked to a CSM on orbit as shown by Figure II.G-1. It should be noted that in its baseline configuration both the audio and TV parts of the system are dependent on the CSM for operation. Further descriptions will be provided on each of the seven basic portions of the system with a special description on audio contact to the ground in case of a failed CSM. System descriptions are to a large extent presented as single figures consisting of a block diagram and associated black box descriptions. Special features are pointed out in the body of the text.

a. Data Systems. The ATM and AM PCM data systems both made use of equipment developed for and flown on earlier programs. Both systems were used to process, record, and transmit housekeeping and scientific data. The systems shown in Figures II.G-2 and II.G-3 both had fixed formats for both real-time transmission and delayed broadcast from recordings. The AM system provided more recorded data flexibility than the ATM by having various portions of its complete output selectable for recording.

The ATM reliability goals were accomplished by incorporating installed redundant equipment for all functions considered critical or high risk. Selection between the redundant elements could be made by ground command or crewman selection from the ATM C&D console.

The AM used essentially the same approach with the in flight maintenance capability being provided for the tape recorders. These were installed in operating positions and any data required could be recorded on any one although during certain experiment operating modes all three were required simultaneously. For in flight maintenance procedures spares were carried in the SWS and installed during flight. Additional AM recorders were brought up to the SWS on manned flight SL-3. An AM tape recorder repair kit was brought up on manned flight SL-4.

The RF portion of the ATM telemetry subsystem was used to telemeter real-or delayed-time PCM data from the ATM systems and experiments to the STDN. Input switching enabled either transmitter to transmit either the PCM real-time format or the PCM delayed-time (recorded) format. Both transmitters could transmit the same data (i.e., real-time format or delayed-time format) simultaneously.

Appropriate modulation and antenna selection was accomplished by either ground command or astronaut control. The antennas were switchable so whichever element exhibited the higher gain at a given spacecraft look angle to the ground, that element could be selected for telemetry transmission.

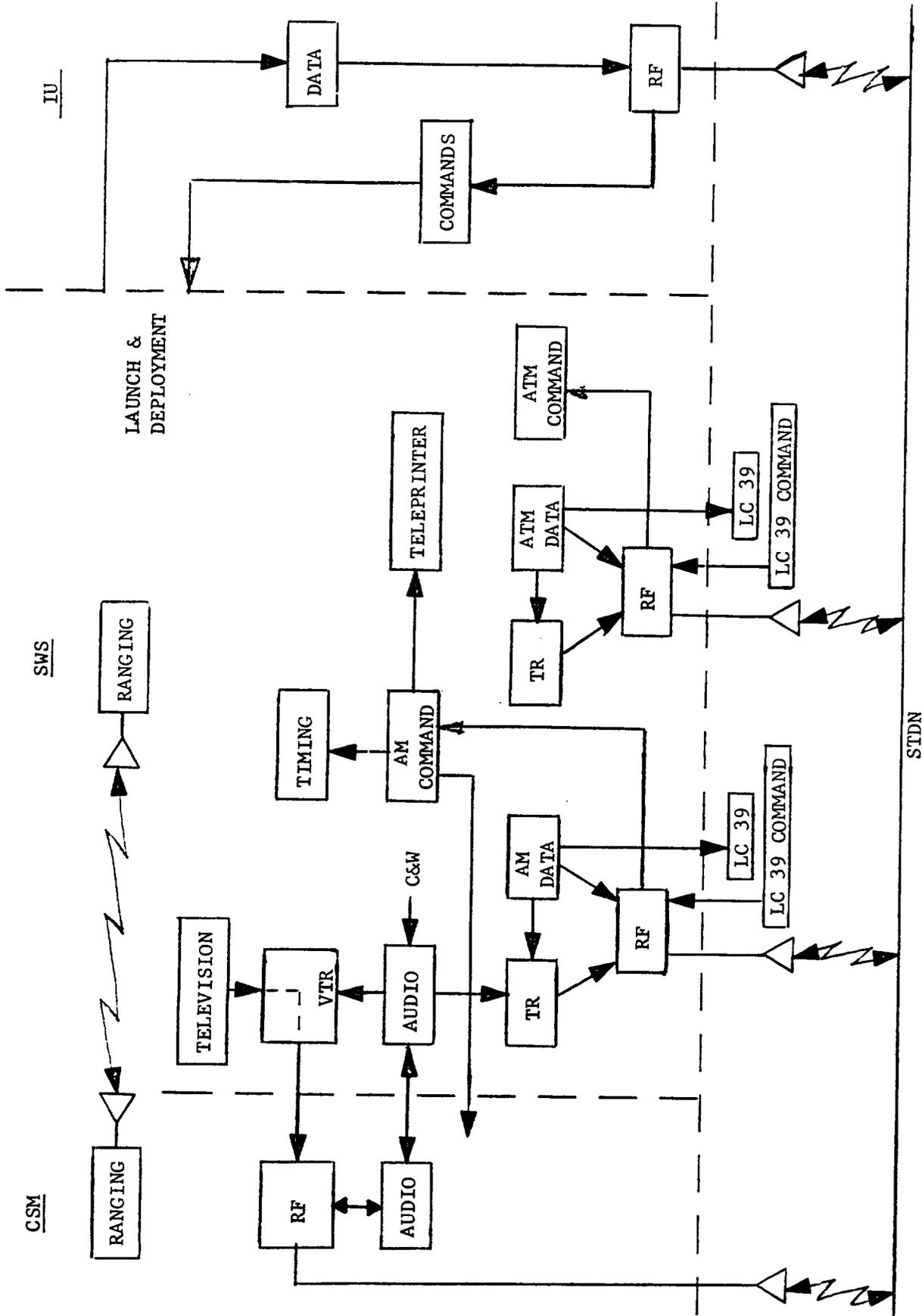


Figure II.G-1. SWS I&C System Diagram

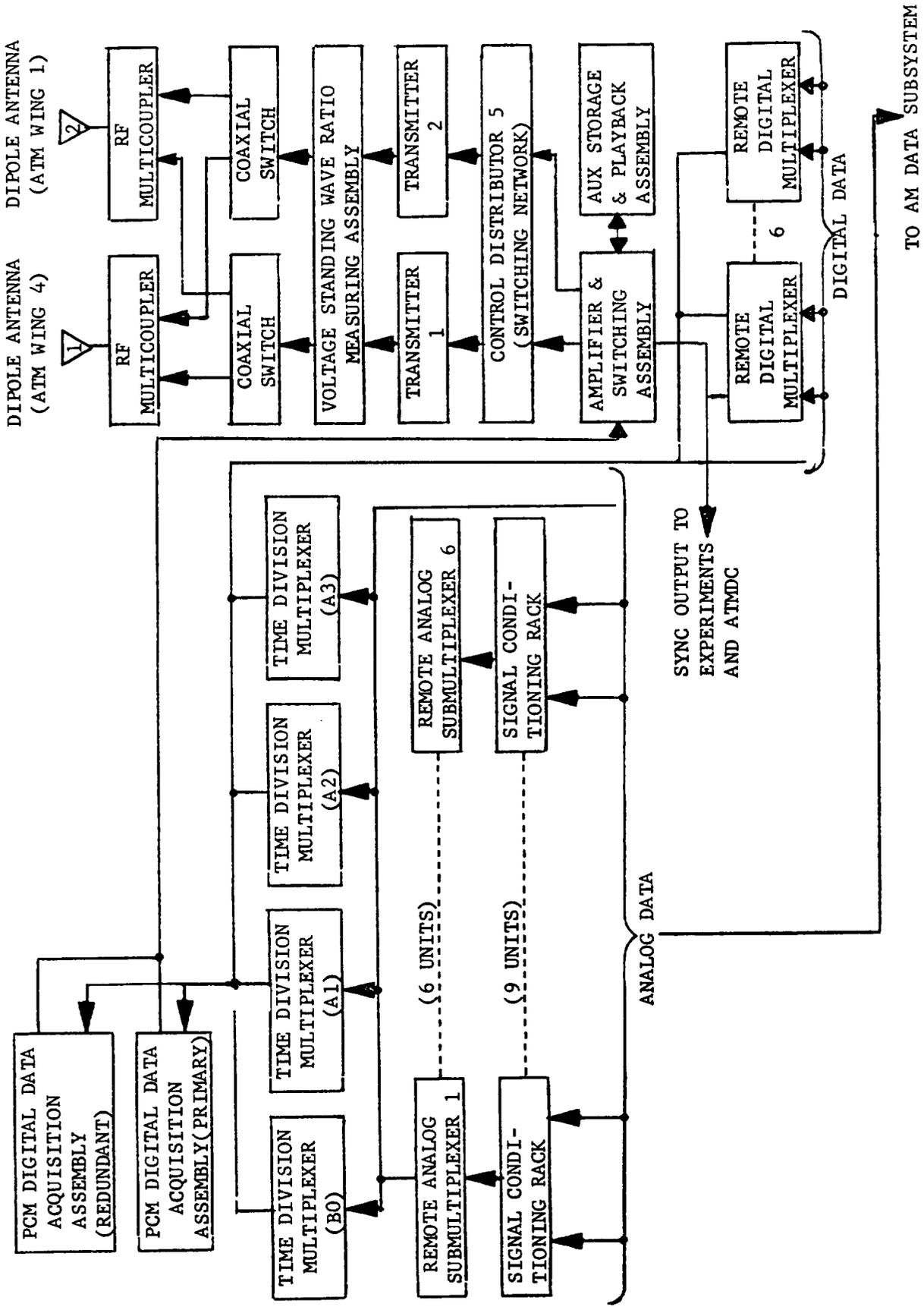


Figure II.G-2. ATM Data Subsystem Functional Block Diagram (Sheet 1 of 2)

SIGNAL CONDITIONING RACK: Conditions analog measurements to be compatible with RASM inputs of 0 to 20 mVDC and provides transducer excitation voltage.

REMOTE ANALOG SUBMULTIPLEXER: Samples 60 low level (0 to 20 mVdc) input channels and provides amplified PAM (0 to 5V) output to time division multiplexer.

TIME DIVISION MULTIPLEXER: Samples 234 high level (0 to 5 Vdc) signals from the RASM, from direct analog data sources and experiment sub-commutators. Sampled data is interleaved with amplitude reference data. Resultant PAM output signal is routed to the PCM Digital Data Acquisition Assembly.

REMOTE DIGITAL MULTIPLEXER: Samples digital data and accepts 100 bits of information; temporarily stores this data in 10 magnetic core registers as 10-Bit Digital Words. The words are transferred one at a time to a parallel storage register and held there until the PCM assembly is ready to accept them.

PCM DIGITAL DATA ACQUISITION ASSEMBLY: Performs A-D conversion, sync generation and formatting. Digitizes analog signals and encodes them into 10-bit digital form, combines them with digital inputs from the remote digital multiplexers and digital data sources. Generates a 144 kHz timing signal from which sync rates of 72 kHz, 3.6 kHz, and 4 pps are derived. An output format of 30 frames is produced. Each frame contains time slots for 60 10-bit words, for a total of 1800 words resulting in a master frame of 250 milliseconds duration.

AMPLIFIER AND SWITCHING ASSEMBLY: Provides switching of the sync signal between primary or redundant line drivers. Also selects tape recorder outputs from either primary or redundant PCM assembly for transmitter modulation. Has manual and ground control.

AUXILIARY STORAGE AND PLAYBACK ASSEMBLY: Accepts parallel 10-bit PCM data and sync signals from PCM assembly via the ASA. Extracts 400 words/sec of preselected PCM assembly data and records at 4 Kbps for 90 minutes. Playback of stored data at 72 Kbps occurs in 5 minutes. Two recorders are provided and are not replaceable in flight. Has manual and ground control.

TRANSMITTER: Provides a carrier for real time and delayed time PCM. The units are solid state operating at VHF frequencies of 231.9 MHz and 237.0 MHz. Has manual and ground control.

VOLTAGE STANDING WAVE RATIO MEASURING ASSEMBLY: Measures incident and reflected RF power at transmitter outputs for telemetering to ground.

COAXIAL SWITCHES AND RF MULTICOUPLER: Permits each transmitter to be connected to either of two antennas or allows both transmitters to be simultaneously connected to either antenna. Has manual and ground control.

ANTENNA: Dipole-type with linear polarization; minimum absolute gain of -6 dB over 75% of radiation sphere; antenna patterns complementary and nearly omnidirectional. One antenna is located on ATM Solar Wing 710 and the other on ATM Solar Wing 713.

Figure II.G-2. ATM Data Subsystem Functional Block Diagram (Sheet 2 of 2)

SIGNAL CONDITIONER: Conditions analog and discrete measurements to be compatible with both the high and low level multiplexers and the onboard displays.

HIGH-LEVEL MULTIPLEXER: Samples up to 32 analog (0 to 5 Vdc) and 40 bilevel (0 to 28 Vdc) digital signals.

LOW-LEVEL MULTIPLEXER: Samples 32 low level (0 to 20 mVdc) input channels and provides amplified PAM output to the PCM Interface Box or the PCM Programmer.

PCM INTERFACE BOX: Conditions high and low level multiplexer outputs for processing by the PCM Programmer. Subframes 2, 3, and 4 are made available for tape recording at 5.12 Kbps RZ signal; also, provides redundant circuit and switching capability. Has manual and ground control.

PCM PROGRAMMER: Digitizes analog signals, serially combines these signals with digital and sync data and formats data into 51.2 Kbps NRZ serial output. Subframe 1 (5.12 Kbps RZ signal) is made available for tape recording. The PCM Programmer provides a clock rate of 409.6 kHz. Has manual and ground control.

RECORDER-REPRODUCER: Records PCM on track A, voice only on track B. Recording time three hours; plays back during rewind at 22 times recording speed. Input PCM is either subframes 1, 2, 3 or 4, or experiment PCM. Has manual and ground control.

DC-DC CONVERTERS: Provides regulated power at 24 Vdc, -24 Vdc, and 5 Vdc to the Data Subsystem. Has manual and ground control.

TRANSMITTER: Provides a carrier for real time PCM, delayed time PCM and delayed time voice. The units are solid state operating at VHF frequencies of 230.4 MHz, 246.3 MHz and 235.0 MHz (the 2-W unit also transmits at 230.4 MHz). The 2-W transmitter is the only one used during launch. Has manual and ground control.

QUADRIPLEXER: Permits the simultaneous operation of the transmitters and the command receivers with the antennas.

COAXIAL SWITCH: The switches are used to select the following: UHF Stub or Discone, either discone, 2-W or 10-W 230.4 MHz transmitter. Has manual and ground control.

STUB ANTENNA: One stub antenna is used for the AM Command Subsystem only. The other stub antenna is used for both data and command.

DISCONE ANTENNA: One discone antenna is used for both data and command systems. Antennas are selectable by manual and ground control.

The need for one or more omnidirectional radiating elements for downlink data was realized early in the ATM program. Preliminary consideration was given to mounting these antennas at the end of booms extending out from the ATM rack structure. However, the concept of using the solar panels as extended antenna mounts soon evolved, and was accepted. The telemetry antenna design first given serious consideration was the use of a notch cut into the edge of a dummy solar panel, or a slot cut out of the dummy solar panel mounted on the end of the solar panel wings. The design was, mechanically, compatible with the solar panels but eventually had to be replaced because of unsymmetrical antenna patterns including sharp nulls.

The notch concept was finally discarded in favor of simple dipoles. The flown configuration had two dipoles mounted in planes that were mutually perpendicular, thus avoiding overlap of pattern nulls. They displayed better overall patterns and were still relatively simple mechanical devices, with sufficient mounting flexibility to favorably orient the antenna pattern.

The AM RF system included two types of antenna, namely stub antennas and discone antennas. Because the discone antennas were folded inside the shroud, the stub antenna mounted on a fixed portion of the shroud was designed to be used during launch in conjunction with the 2 watt transmitter. Use of the 2 watt transmitter during the launch phase avoided the possible loss of data due to corona in the 10-watt transmitter.

In the transition from the WWS to the DWS concept of Skylab, consideration was given to using all 2 watt transmitters. Subsequent analysis determined the 2-watt transmitter to be inadequate for continuous orbital operations, because these low-level transmitters resulted in marginal signal levels at maximum slant range for both the 220 and 260 n mi trajectory altitudes, being considered at that time. The VHF coverage of a 260 n mi, 50 degree inclination mission was reduced from 28.1 percent of flight time to 21.2 percent, or nearly a 25 percent decrease. The analysis compared the 2 watt transmitter to a 10 watt transmitter. It became apparent that an increase in the power output of the transmitters was necessary to increase coverage and permit signal acquisition at maximum slant range. Use of a 10 watt transmitter represented a seven dB increase in signal margin. This power level yielded positive signal margins for less than nominal link conditions. The 10 watt transmitter was subsequently defined for the AM telemetry system and became the orbit configuration. As mentioned earlier, a 2 watt transmitter was retained and used during the launch phase.

b. Command Systems. The ATM command system hardware was a carryover from the Saturn program. The command receiver operated at 450 MHz and after demodulating the RF signal, provided a dual phase-shift keyed (PSK) audio output to the decoder or a 72 Kilo Bits per second (Kbps) wave train to the digital computer memory load unit. The latter signal allowed the ground to reload the ATM digital computer

memory if required. The output of the decoder was either digital inputs to the ATM digital computer or digital commands processed by the switch selectors. As noted in Figure II.G-4, the switch selectors and the digital computer could also be accessed by an onboard keyboard mounted on the ATM C&D console. The keyboard was capable of implementing the same commands that were available to the ground. The command system was redundant and could be operated in parallel or individually.

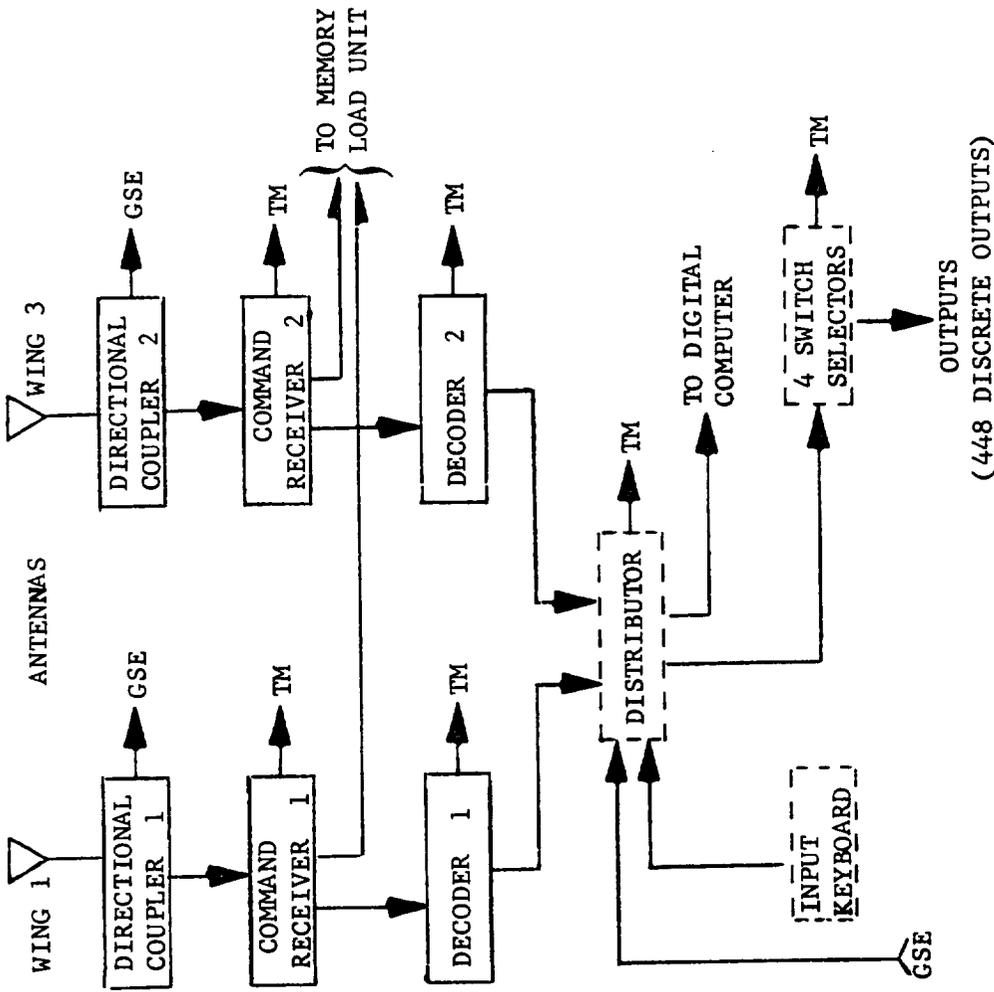
The original design of the ATM command system consisted of one-half the redundancy shown in Figure II.G-4. To meet the program reliability requirements the system components were configured to provide two independent parallel systems connected in active redundancy although only one operational system was required for processing the command data transmitted by the STDN. System design allowed the STDN to address either or both independent systems. The ATM command system was activated via an AM command system function.

From the early design stages of the ATM, when the ATM was to be a free-flying module to be docked to the WWS cluster, the need for one or more antennas was required on the ATM for command reception. It was desirable that these devices be omnidirectional because they were to be effective with the cluster in a variety of attitudes. Preliminary consideration was given to mounting these antennas at the end of booms extending from the ATM rack structure. However, the concept of using the ATM solar panels as extended antenna mounts soon evolved and was accepted.

Three antenna configurations were considered: a scimitar element, a fixed (bent) dipole element, and a deployable dipole element. The bent dipole antenna (also referred to as a quadrant antenna), when compared to a scimitar element, showed a more uniform antenna pattern with only minor nulls in the pattern, whereas the scimitar showed sharp peaks and deep nulls in its pattern. The dipole element thus was a more desirable antenna, being more omnidirectional. The dipole element also proved to have a better gain distribution (i.e., percentage of spherical coverage versus antenna gain) than did the scimitar antenna.

Considering the above and the fact that the bent dipole was much smaller and lighter than the scimitar element, which required a heavy ground plane, the bent dipole antenna was selected to be mounted on an antenna panel at the end of ATM solar panel 710.

The second element of the redundant antenna system was to be a deployable dipole element located on the end of ATM solar panel 712. This element was given initial rejection on the basis that the added element was not really necessary for adequate coverage and also that it would require deployment that would be less reliable. However, the second element when added in quadrature to the first element (on panel 710) and being in a plane perpendicular to the first element provided an exceptional complement for command coverage.



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COMMAND ANTENNA The two stub antennas are independently hardwired to each command receiver. Antennas are physically mounted in quadrature such that perpendicular element is predominantly crosspolarized with respect to the other antenna element.

DIRECTIONAL COUPLER Couples signal energy from antenna to command receiver; couples ground equipment test inputs to the receiver during prelaunch checkout.

COMMAND RECEIVER Receives RF signal, down converts, discriminates and provides isolated PSK composite output to the decoders or a 72 Kbps wave train to the Memory Load Unit.

COMMAND DECODER Decodes PSK composite signal, verifies resulting code signal, and issues output based on coded signal to the switch selectors or the digital computer. A verification pulse is transmitted confirming message has been correctly received and decoded.

Figure II.G-4. ATM Command Subsystem Functional Block Diagram

The AM command system also operated at 450 MHz but accepted only those commands with the proper vehicle address code. As noted in Figure II.G-5, redundant receivers and decoders were provided with the capability of switching from one system to the other automatically or by ground command. In addition to providing 544 discrete commands, and update the timing system, the command system also processed uplinked messages to the AM teleprinter providing the crew with a hard copy of data transmitted from the STDN.

During the launch and initial unmanned activation period of Skylab, command reception was accomplished using the command and launch stub antennas located on the AM FAS. Following deployment of the discone antennas, command reception was switched from the stub to the discone antennas.

The stub antennas were modified Gemini elements designed for command reception in the 440 to 460 MHz frequency range (450 MHz nominal). The electrical characteristics of the stub elements were basically unchanged except the stubs which were $\lambda/4$ wavelength long before the DWS ended up as a $\lambda/2$ stub element in its final configuration.

The discone antennas, designed for command reception at 450 MHz nominally, remained unchanged in electrical characteristics since their inception during the early program period. Each discone element was located on the ends of booms that were deployed subsequent to Skylab orbital insertion and PS jettison. To establish the best possible configuration for optimum coverage, the location and length of the booms were varied during the program.

c. Ranging Subsystem. During the CSM rendezvous and docking phase, the AM ranging system was used in conjunction with the CSM Apollo ranging system to compute and display the range between the CSM and the SWS. The AM ranging system consisted of a helix element ranging antenna, a Very High Frequency (VHF) transceiver, and a range tone transfer assembly (RTTA). A block diagram of the AM ranging system is shown in Figure II.G-6.

During the period of WWS to DWS transition, an AM ranging system was introduced to work in conjunction with an established CSM Apollo three-tone ranging system. System design was based on the technical restraints of the Apollo system and the Skylab mission requirements. As the mission requirements (e.g., tracking range, SWS attitude during rendezvous, CSM to SWS orientation during rendezvous) changed, so did the conceptual design of the AM ranging system.

Several options were considered in establishing the ranging antenna element(s) type and locations. Based on an early mission sequence requirement that the SWS would be in the Z-LV attitude for one-orbit from noon-to-noon and in the SI attitude for the remainder of the rendezvous, it was concluded that it would be impossible to generate the required antenna coverage from the AM without the addition of boom supported antennas.

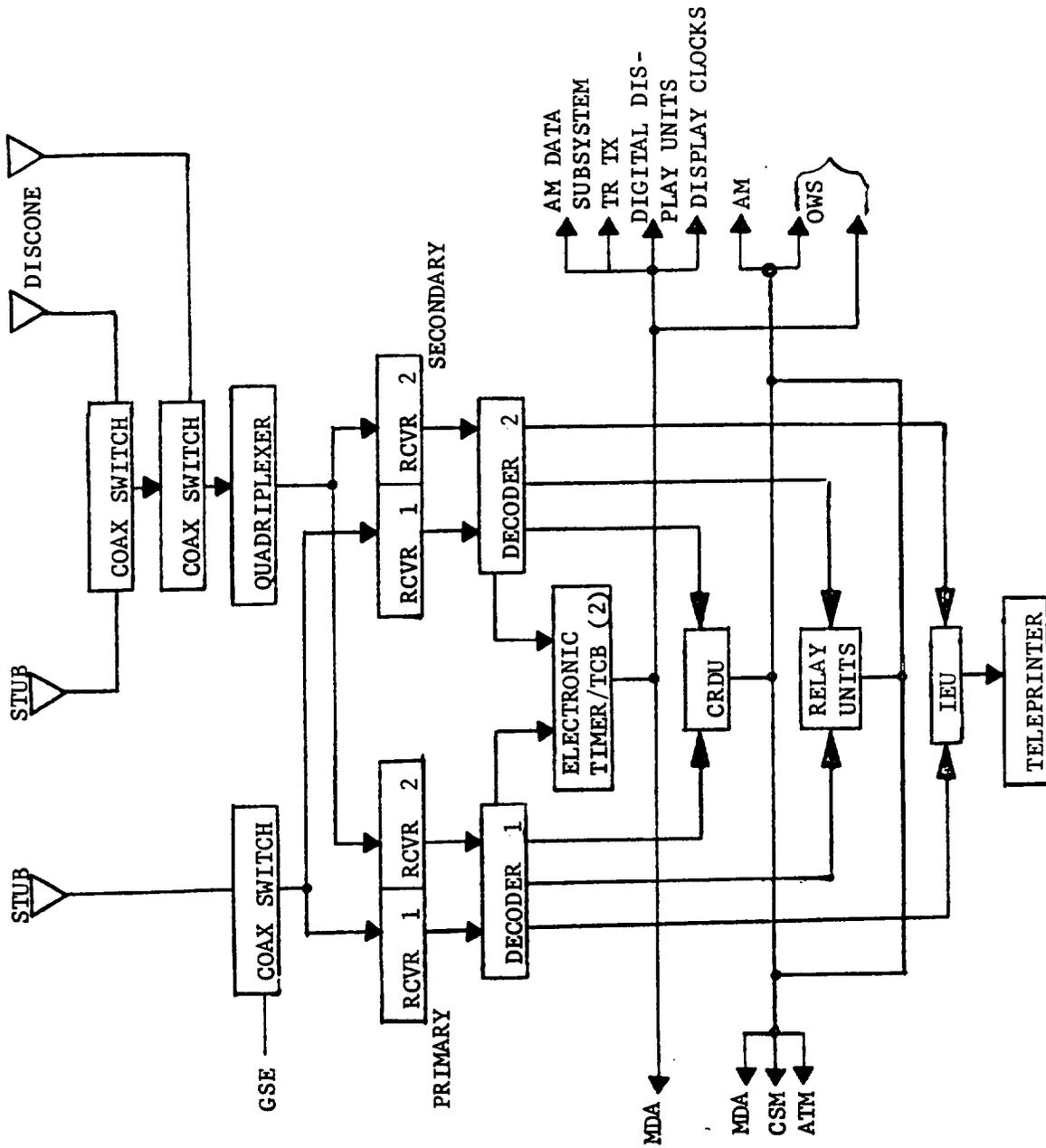


Figure II.G-5. AM Command Subsystem Functional Block Diagram (Sheet 1 of 2)

STUB ANTENNA: One stub antenna is used for the AM command subsystem only. The other stub antenna is used for both data and command. Has manual and ground control.

DISCONE ANTENNA: A discone antenna is used for both data and commands. Has manual and ground control.

COAXIAL SWITCH: The switches are used to select the following combinations: UHF Stub or Discone, either discone, GSE input or stub.

COMMAND RECEIVER: Receives RF signal, down converts, discriminates and provides PSK composite output to the decoders.

COMMAND DECODERS: Decodes PSK composite signal, provides digital data output to the time reference system, CRDU or teleprinter, or a discrete pulse to the relay modules. A verification pulse is transmitted confirming that the message has been correctly received and decoded. Has manual and ground control.

RELAY MODULE: Receives discrete pulses from decoder and operates latching relays. Each relay provides output to indicate its status.

COMMAND RELAY DRIVER UNIT: Converts serial digital data from receiver/decoder into real time commands for SWS subsystems, and experiments. Provides output to telemetry to indicate specific command process. Has manual and ground control.

ELECTRONIC TIMER/TCB: Provides timing to the data subsystem, countdown of time to go to equipment reset (Tx); automatic control of redundant DCS receiver/decoder (Tr), and GMT data to EREP and onboard displays. Has ground control.

INTERFACE ELECTRONIC UNIT: Decodes data into proper format for use by teleprinter.

TELEPRINTER: Prints 30 characters/line hard copy of messages at a speed of one line per 970 m Sec. Has manual and ground control.

TRANSCIEVER ASSEMBLY: Receives a carrier frequency of 259.7 MHz transmitted from the CSM. Demodulates the audio range tone and inputs it to the RTTA. Accepts the audio range tone output from the RTTA and modulates a 296.8 MHz carrier.

RANGE TONE TRANSFER ASSEMBLY: Accepts demodulated audio range tones from the receiver. The RTTA detects and reconstructs the range tone signal (medium: 3.95 kHz square wave; coarse: 3.95 kHz/247 Hz module-two sum square wave; or fine: 31.6 kHz square wave) which is then used in the RTTA to modulate the transmitter carrier of the Transceiver Assembly.

ANTENNA: A 5 turn helix is used for both receiving (259.7 MHz) and transmitting (296.8 MHz) signals from the Transceiver Assembly. The antenna provides high gain in a narrow beamwidth sector (50 degrees).

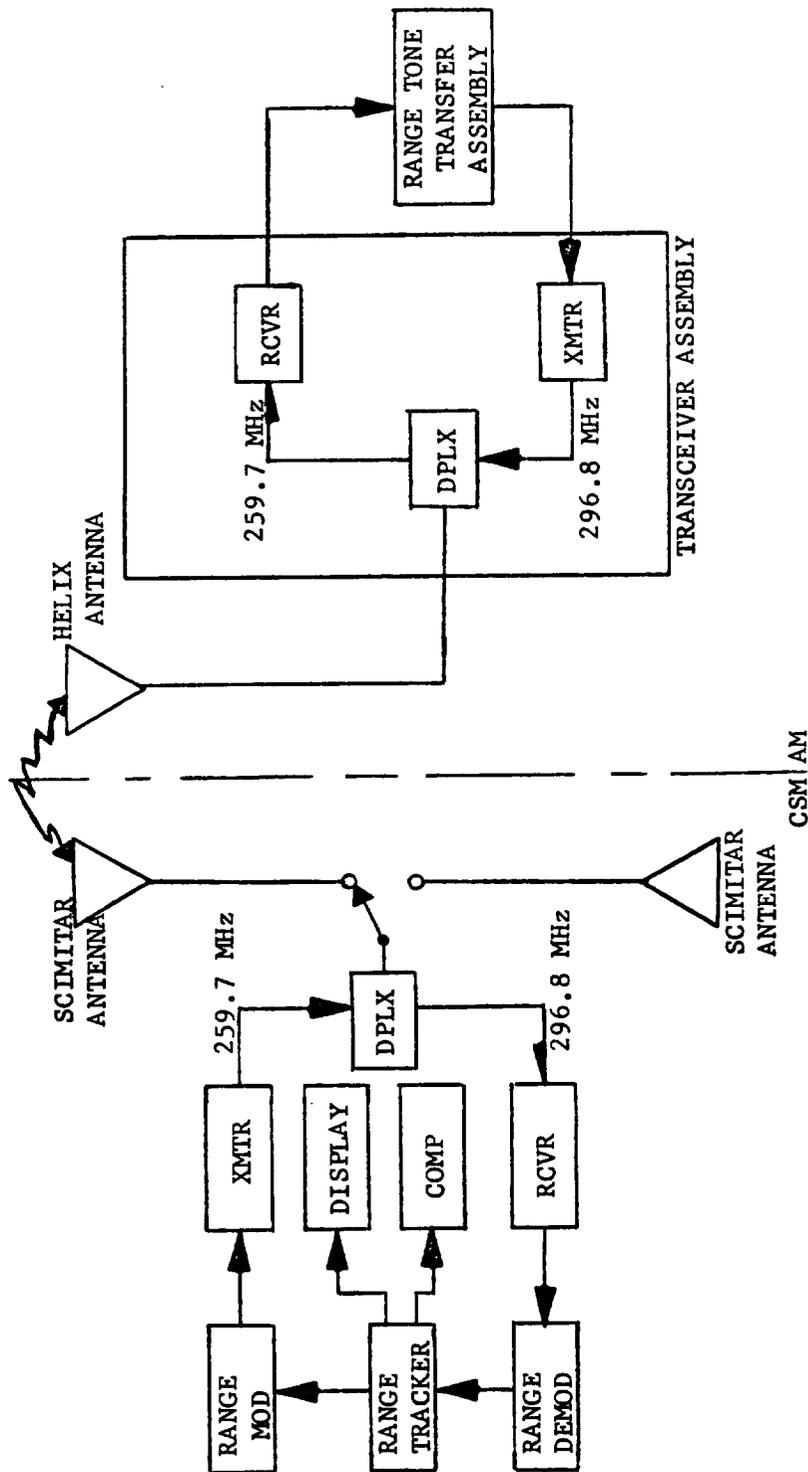


Figure II.G-6. SWS/CSM Ranging Subsystem Functional Block Diagram

Several antenna configurations were considered. Adequate antenna coverage could be provided for a SI rendezvous (i.e., no Z-LV) with two low gain helices each mounted on six-foot deployable booms extending from the AM STS and one high gain helix deployed on a shorter boom from the STS below the longitudinal (X-axis) axis of the SWS. Boom mounted antennas on the AM STS would also provide adequate coverage with a sequence requirement for SWS Z-LV attitude for two orbits (maximum) with the OWS leading. This was the final attitude requirement established for rendezvous.

The deployed boom concept for the ranging antennas was rejected for the fixed mounted antenna concept, so no movable or deployable appendages would be necessary to activate the antenna system.

Continued analysis and finalization of mission sequence requirements for rendezvous, led to the definition of a single helix 5-turn element antenna. Its location was to be fixed mounted on the ATM DA, such that after the DA was deployed, positioning the ATM above the MDA in its sun-oriented on-orbit position, the ranging antenna would be located approximately over and on the +Y side of the MDA axial docking port, and below the main body of the ATM. The antenna was oriented such as to provide coverage in the X-Z plane and in the +X, +Z quadrant of the plane of rendezvous and docking. The range was 300 n mi with the SWS in the Z-LV attitude. The antenna element was predominantly circularly polarized and was used for both receiving and transmitting. The 3 dB beamwidth was 50 degrees with peak gain of 9 dB.

d. Audio System. The audio subsystem was designed to provide intercom capability for the crew within the OA and/or while engaged in EVA and to provide two-way communication between the STDN ground stations and the crewmen in real time. Delayed time downlink voice was also provided. In addition, the subsystem supports the gathering of biomedical data and operation of the C&W subsystem. See Figure II.G-7 for a functional block diagram and a listing of major components.

For normal communication, the operation of the system required the presence of the CSM because the system was dependent on the CSM audio amplifiers and transmitter/receivers for on-orbit intercom and real-time communication with the ground. Because RF communication with the ground was limited on average to approximately 30 percent of the time, the capability to record voice was provided in the AM. A tape recorder amplifier was provided in the Audio Load Compensator (ALC) taping the voice signal from the earphone lines. The voice was recorded on the second track of the AM data recorder and played back at high speed when over a ground station.

Two independent channels, A and B, provided redundant voice communication capability throughout the OA. One channel was configured to provide intercom and real-time transmission with the ground and the second channel was allocated for the recording of voice. Voice inputs

C-3

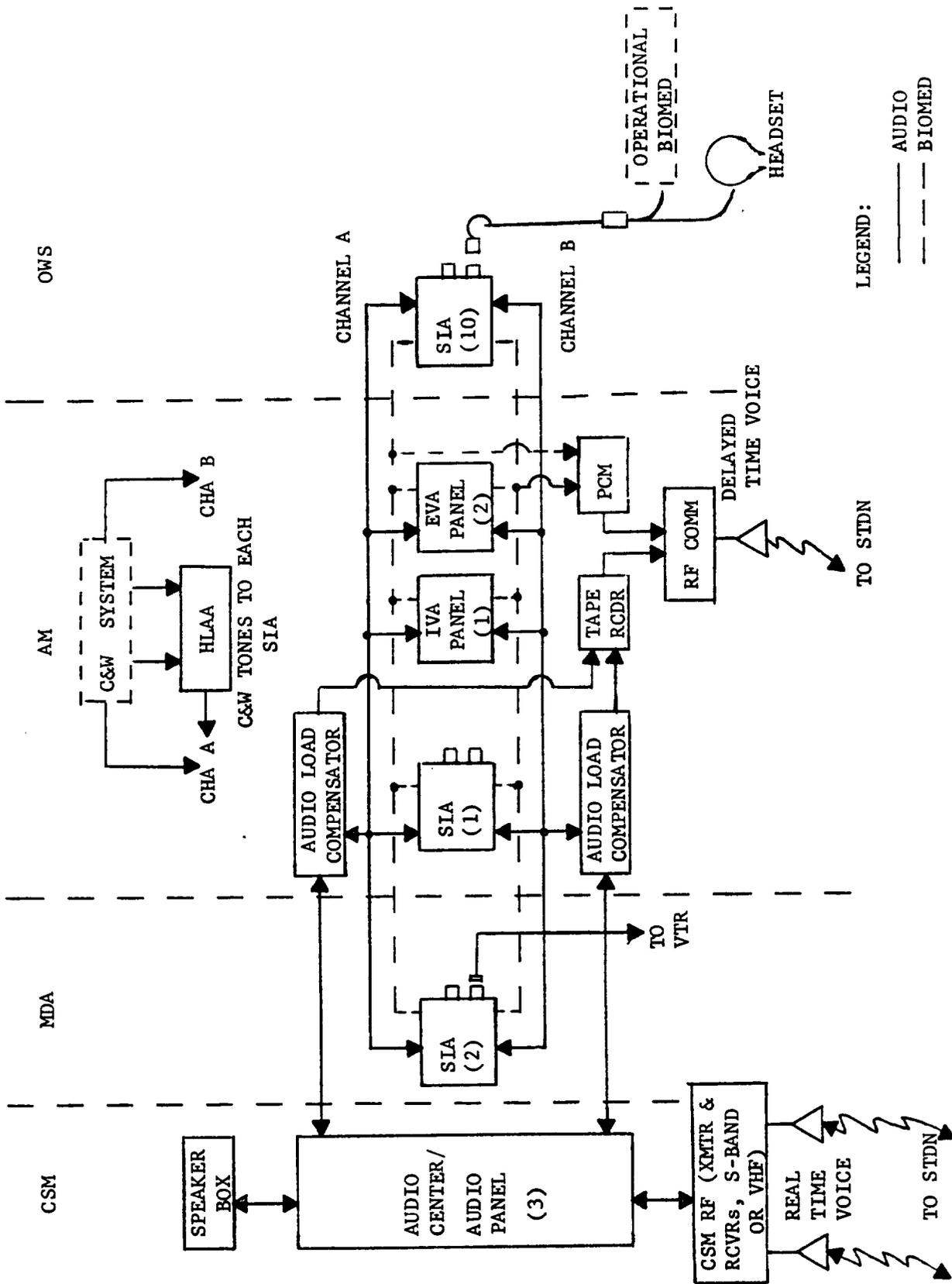


Figure II.G-7. Orbital Assembly Audio Subsystem Functional Block Diagram (Sheet 1 of 2)

SPEAKER INTERCOM ASSEMBLY: The SIA contains a speaker and a microphone operating in a simplex mode, provides control for crewmen inter-communication as well as communication with ground, and provides receptacles for communication umbilicals, contains controls for microphone and transmitter keying, call channel selection and tape recorder, provides audible and visual indications from the C&W subsystem. A high level C&W signal bypasses the SIA amplifiers and is coupled to the SIA speaker.

CREWMAN COMMUNICATION UMBILICAL: The CCU connects the headset and the operational biomedical data to the SIA receptacle. A volume control and a transmitter keying switch are provided as integral parts of the umbilical.

LIGHT WEIGHT CCU: The LWCCU is functionally identical to the CCU except no biomedical wiring is included. A detachable control head containing a volume control and a keying switch is provided allowing two umbilicals to be connected in series.

COMMUNICATION CARRIER HEADSET: The communication carrier headset contains two microphones/amplifiers and two earphone transducers and can be used for suited or unsuited operations.

LIGHT WEIGHT HEADSET: The LMHS contains only one microphone/amplifier and one earpiece and is used in the shirt sleeve mode.

AUDIO LOAD COMPENSATOR: The ALC buffers the CSM Audio Center to the SWS audio distribution bus, provides power amplification, automatic volume control and isolation for the headset and the microphone lines. Audio inputs to the AM tape recorder are provided.

CSM AUDIO PANEL/AUDIO CENTER: Provides amplification and AGC of microphone signals from the SWS audio channels. Each channel is interconnected to separate audio panel/audio centers. In the intercom privacy mode, the CSM microphone output is further amplified by the earphone amplifier whose output is connected to the SWS ALC earphone circuit. This output signal is controlled by volume controls on the audio panel. Other switches and controls on the audio panel routes signals from the second SWS audio channel to CSM RF for duplex communications with the ground. The third audio panel/audio center is connected to a CSM speaker box whose functions are similar to the SWS SIA.

CSM RF: Provides duplex real time voice communication with the STDN via either S-Band or VHF transceivers. All switching and volume level controls are located on the audio panel.

Figure II.G-7. Orbital Assembly Audio Subsystem Functional Block Diagram (Sheet 2 of 2)

into an SIA or EVA/IVA panel via headsets were routed to the CSM via the microphone amplifiers of the ALC. In the CSM the signal was amplified and returned to the SWS ALC via the headset line amplifier. The signal was then distributed to any active SIA or headset connected to this channel. For real-time communication with the ground, the CSM S-band transmitter/receiver was switched to the proper channel via the CSM audio panels providing duplex voice communication with a crewman from any audio station on the SWS.

In the course of the Skylab program the audio system underwent significant changes as the program requirements were revised from the WWS to DWS by LM deletion and finally an attached ATM. Although the interface with the CSM voice communication system did not change the system originally included a secondary voice mode that used airlock audio equipment and transceivers to provide intercom and a simplex link between the airlock and the STDN.

In the final configuration, the airlock RF voice communication subsystem was deleted which included the VHF transceiver, VHF duplex receiver and peripheral audio equipment. The revised system took advantage of existing communication hardware required by the CSM when flying to and from the SWS. The revised system, as flown, included use of the CSM S-band system for duplex communication, backed up by the CSM VHF communication equipment. Redundant, ALCs were provided in the SWS providing separate buffer amplifiers for the microphone and earphone lines in addition to providing voice record capability as previously described. As new experiment and operational requirements were developed, the quantity and locations of the SIAs continued to be changed. During this period a study was made on the design requirements for the SIA and whether it should be a two-box unit or a one-box unit for providing channel switching, headset connection, microphones, speakers and associated amplifiers, tape recorder controls, biomedical monitoring channels and interface with the C&W system. Incorporation of all of these functions in one box resulted from studies conducted by NASA, module contractors and crew preference.

e. Television System. The Skylab TV system consisted of a TV bus routed through the MDA, AM, and OWS for record/transmission of scenes from a portable field sequential color camera and a tie-in with the five ATM experiment cameras for the retrieval of scientific data, (see Figure II.G-8). The video output from any one of these cameras was selectable for downlink transmission to earth via the CSM S-band transmitter. Because continuous contact with ground stations was impossible due to the low nonsynchronous orbit of Skylab, a video tape recorder was provided capable of recording 30 minutes of video data and playback at the same record speed via the same S-band transmitter.

In the SWS, five camera plug-points (TV input stations) were provided for use by the color camera so that almost all manned areas internal to the SWS could be observed. One of these stations was located so that the astronaut's EVA could be observed. In addition, a special

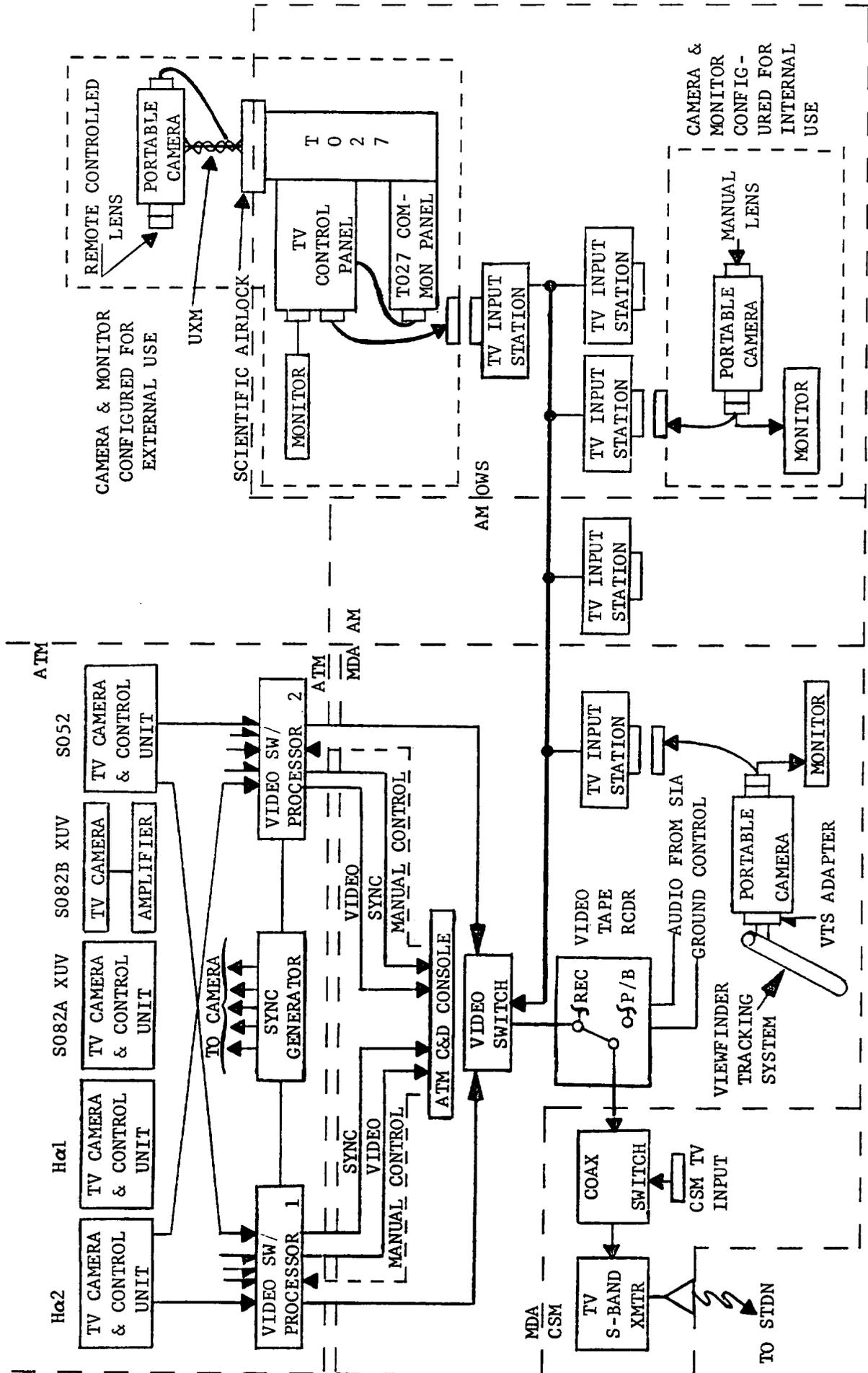


Figure II.G-8. Orbital Assembly Television Subsystem Functional Block Diagram (Sheet 1 of 2)

TV INPUT STATION: Conditions portable TV camera video signal levels to interface with unified S-band FM transmitter.

PORTABLE TV CAMERA: Provides internal and external TV coverage; hand-held or fixed to universal mount for internal use, fixed to SAL extendable boom for external use; manual controlled lens, portable monitor, and 30-ft cable for internal use.

PORTABLE TV MONITOR: The monitor with necessary controls is used to assist the crewman to focus and operate the portable TV camera.

TV CONTROL PANEL: Controls the portable TV camera when camera is mounted on Experiment T027 boom; control functions are zoom, iris, focus, and automatic light control sensitivity.

T027 COMMON PANEL: Points the portable TV camera in azimuth and elevation when camera is mounted on Experiment T027 boom.

VIDEO SWITCH: Conditions ATM video signal levels to interface with the Unified S-Band FM Transmitter; provides manual signal selection between the portable TV camera or the video switcher/processor 1 or 2.

Hα1, Hα2, S082A XUV, S082B XUV WHITE-LIGHT AND S052 WHITE-LIGHT CORONAGRAPH CAMERAS: Five ATM TV cameras used by the crewmen for aiming and adjusting experiments.

SYNC GENERATOR: Provides sync drive signals to the ATM cameras and the ATM C&D console.

VIDEO SWITCHER/PROCESSOR: Provides sync drive signals to the ATM cameras and the ATM C&D Console; adds sync to camera signals; isolates ATM video ground for transmission.

ATM C&D CONSOLE: Selects and displays ATM video signals.

VIDEO TAPE RECORDER: Records video and voice for playback. Controls for crewmen and ground to record, position tape and apply headwheel drive power. Crewman control can also turn recorder off. Playback is controlled from the ground.

CSM COAXIAL SWITCH: Switches the video signal to the Unified S-Band FM Transmitter from either the SWS video bus or the CSM camera output.

UNIFIED S-BAND FM TRANSMITTER: Transmits video signals from dc to 2-MHz bandwidth.

Figure II.G-8. Orbital Assembly Television Subsystem Functional Block Diagram (Sheet 2 of 2)

adapter was provided for the camera to be mounted on the Experiment T027 boom (remotely controlled by the crewmen inside) to make observations outside the spacecraft. A video switch located in the MDA provided the capability to switch from the TV bus to the ATM cameras for recording or transmission to ground. The ATM TV video was the same scenes as monitored by the crew on the ATM C&D console. A unique feature of the video tape recorder was its capability to interweave the crews voice signal into the video signal format, eliminating the necessity for a separate RF downlink for audio. Audio inputs to the tape recorder was accomplished by interconnecting a cable from the SIA connector normally used for headset operation to the Video Tape Recorder (VTR) audio input connector.

The evolution of the TV system was one whereby new requirements were identified over the course of the program. As the SWS configuration changed from the WWS to the DWS, trade-offs were initiated between using preinstalled cables or drag-in cables.

The system trade-offs resulted in a configuration using a single preinstalled coaxial cable bus through the SWS with amplifier stations for connecting the TV camera. The amplifiers were found necessary due to losses in the cable length required to cover the entire SWS. The Skylab program made use of the best cable available for interior use on a manned vehicle, RG-210, and developed the necessary isolated (floating shield) coaxial connectors.

A later requirement for transmitting ATM signals was met by the installation of a switch in the MDA to select between signals originating in the MDA and either of two ATM signals. The switch included amplifiers to achieve a proper interface level for the transmission of the ATM signals. The ATM was modified from its baseline closed circuit TV system design by the addition of equipment to add a synchronization signal to the TV signal and ground isolation to eliminate a ground loop to ATM structure.

System evaluation led to a new program requirement that allowed the camera to be mounted outside of the SALs in the OWS on the Experiment T027 universal extension mechanism. This provided coverage of scheduled EVAs to the ATM and also a means of surveying the exterior of a majority of the OA via a remote control panel.

During 1971 reviews were made of the feasibility of incorporating a VTR in Skylab. Late in the year, the decision was made to incorporate a recorder from the Earth Resources Technology Satellite Program modified for incorporation in a manned space vehicle with provisions for some manual control.

A final system change initiated early in 1972 was to transmit by television the scenes of the VTS of the EREP.

3. Interface. The control of interfaces was an important technical aspect in the formation of the Skylab I&C system. At the time of liftoff 53 ICDs were used to control the wide variety of interfaces that were peculiar to the I&C system.

The method generally followed in the preparation of ICDs and Interface Revision Notices (IRNs) was to have the custodial agency prepare a technical draft, distribute copies for review, consolidate comments received orally or in writing and based on the complexity of the change, conduct a final review with affected parties before submittal for program baseline.

The ICDs reflected a variety of program controls. The types are illustrated by the extensive Level A Audio and Television System Requirements documents encompassing system configuration, system performance, crew interfaces, previous equipment to be used, and operating techniques. The intermodule types represented by the CSM to MDA, and ATM to AM, level A and B respectively, which covered the I&C functions required between modules and the parametric standards of such functions, common SWS hardware to various modules, such as the SIA to the MDA and OWS required a level B document that covered functional requirements and electrical interconnections. A group of tabular documents showing measurements, commands and RF frequencies were generated as level A for the control between centers and are illustrated by the MDA measurement and ATM DCS RF command lists; the I&C checkout interfaces between vehicles and KSC as illustrated by the AM/MDA ESE to Quick Look Data System (QLDS) located in the Operations and Checkout (O&C) building, document; the command and measurement support required by experiments such as M509 Astronaut Maneuvering Equipment to OWS; and the vehicle in flight to ground in the Skylab to STDN document.

Each of the ICDs involved a variety of technical skills, the negotiation of responsibilities on a program effective basis and finally the assurance of testing for compliance. Many of the experiment interface documents for Skylab involved an educational process for organizations outside the program that were unfamiliar with the need and purpose of ICDs.

4. Design Verification. Extensive analyses and tests were conducted on each of the Communication and Data Systems to verify its operational integrity. Analyses were conducted on new hardware design and in hardware applications that were unique to Skylab, i.e., RF communication to ground compatibility. A thorough test program was conducted where feasible, from the black box level to the total system. The magnitude of the Skylab vehicle precluded ground testing of the complete system on the TV and audio system, the on-orbit operation of the docked CSM to the SWS being the first time these systems were activated as an integrated unit. The following paragraphs summarize the more pertinent design verification for each system.

a. Analyses. Because the majority of the Skylab Data and Communication systems were application of design and hardware developed on previous programs, the only formal systems performance analyses were conducted on the antenna coverage and RF circuit margins, the analysis on the Skylab TV System and a RF beat frequency analysis. As with all the other systems comprising the Skylab Vehicle, Failure Modes and Effects Analysis (FMEA), Single Failure Point (SFP), and contingency analyses were conducted on the Data and Communication systems but are not detailed in this report.

(1) Systems Analysis

(a) RF Link Analysis. Up and Down RF link analyses were conducted on the command and telemetry systems for both the AM and ATM. The analyses evaluated the communication links using the expected Skylab trajectory and the STDN ground station operating parameters. Analyses of these links were performed using the Computer Oriented Communications Operational Analysis (COCOA) programs tabulated output carrier margins (Cm). These data then, provided the nucleus for determining the RF link capability associated with communications bar charts, the data-dump/command-gaps, the impact of rendezvous and earth pointing attitude on the telemetry links, and generating the Command Module (CM) analog plots.

A summary of the ATM and AM telemetry and command RF link calculations is shown in Tables II.G-1 through II.G-6. A plus six dB Cm at maximum slant range was required for satisfactory performance criteria (ICD specification). Both AM discones and the ATM Aft dipole exceeded the +6 dB Cm at maximum slant range, using antenna gains achievable over 75 percent of the telemetry antenna patterns. The command links, with the exception of the command stub antenna in conjunction with the Model 27 backup command receiver, exceeded the +6 dB Cm at maximum slant range, using antenna gains achievable over 95 percent of the command antenna patterns.

The trajectory-related RF data generated for the ATM and AM telemetry links by COCOA programs, which used measured and calculated parameters in time increments of 0.2 of a minute, indicated that 95 percent or better of the link computations provided a positive Cm; 84 percent or better provided a +6 dB. The ATM and AM command links indicated 99.9 percent or better provided a positive Cm; 99.8 percent or better provided a +6 dB Cm.

In analyzing the generated link data, it was determined that the telemetry Cms were basically the same when the SWS was in either the Z-LV attitude or in the SI attitude. Also, the principal limiting factor in completing the VHF and Ultra High Frequency (UHF) links, based on a positive Cm, was the maksing data and the two-degree elevation angle constraint, with respect to the ground stations.

(b) Antenna Pattern Analysis. The radiation pattern over the surface of a sphere in a θ, ϕ coordinate system was analyzed

Table II.G-1. ATM Telemetry RF Link Calculations

PARAMETER	FWD ANTENNA LINK	AFT ANTENNA LINK
S/C XMTR POWER (10 WATTS)	$P_t = 40.0 \text{ dBm}$	$P_t = 40.0 \text{ dBm}$
S/C ANTENNA GAIN - FWD & AFT ANTENNA DIPOLES(75% COVERAGE FOR COMPOSITE RHCP & LHCP)	$G_t = - 9.0 \text{ dB}$	$G_t = - 5.3 \text{ dB}$
S/C LOSSES, CALCULATED	$L_x = 4.5 \text{ dB}$	$L_x = 4.5 \text{ dB}$
SPACE LOSSES (FREQUENCY = 235.0 MHz, RANGE = 1,300 n mi)	$L_s = 147.4 \text{ dB}$	$L_s = 147.4 \text{ dB}$
RECEIVE CIRCUIT LOSSES (RF & POINTING ERROR)	$L_r = 2.0 \text{ dB}$	$L_r = 2.0 \text{ dB}$
GROUND STATION ANTENNA GAIN (18-ELEMENT TELTRACE SYSTEM)	$G_r = 19.0 \text{ dB}$	$G_r = 19.0 \text{ dB}$
RECEIVED POWER LEVEL	$P_r = -103.9 \text{ dBm}$	$P_r = -100.2 \text{ dBm}$
RECEIVER SYSTEM SENSITIVITY $T_e = 365^\circ\text{K/B} = 300 \text{ kHz}$	$R_N = -108.0 \text{ dBm}$	$R_N = -108.0 \text{ dBm}$
CARRIER MARGIN	$C_m = 4.1 \text{ dB}$	$C_m = 7.8 \text{ dB}$

Table II.G-2. AM Telemetry RF Link Calculations

PARAMETER	DISCONE LINK 1	DISCONE LINK 2	LAUNCH STUB
S/C XMTR POWER (10 WATTS)	$P_t = 40.0 \text{ dBm}$	$P_t = 40.0 \text{ dBm}$	$P_t = 40.0 \text{ dBm}$
S/C ANTENNA GAIN - DISCONES AND STUB ANTENNA (75% COVERAGE) FOR COMPOSITE RHCP AND LHCP	$G_t = - 5.2 \text{ dB}$	$G_t = - 6.1 \text{ dB}$	$G_t = - 9.2 \text{ dB}$
S/C LOSSES	$L_x = 4.0 \text{ dB}$	$L_x = 3.4 \text{ dB}$	$L_x = 3.2 \text{ dB}$
SPACE LOSSES (FREQUENCY = 235.0 MHz, RANGE = 1,300 n mi)	$L_s = 147.4 \text{ dB}$	$L_s = 147.4 \text{ dB}$	$L_s = 147.4 \text{ dB}$
RECEIVE CIRCUIT LOSSES (RF AND POINTING ERROR)	$L_r = 2.0 \text{ dB}$	$L_r = 2.0 \text{ dB}$	$L_r = 2.0 \text{ dB}$
GROUND STATION ANTENNA GAIN (18- ELEMENT TELTRAC SYSTEM)	$G_r = 19.0 \text{ dB}$	$G_r = 19.0 \text{ dB}$	$G_r = 19.0 \text{ dB}$
RECEIVED POWER LEVEL	$P_r = - 99.6 \text{ dBm}$	$P_r = - 99.9 \text{ dBm}$	$P_r = -102.8 \text{ dBm}$
RECEIVER SYSTEM SENSITIVITY $T_e = 365^\circ\text{K}/$ $B = 300 \text{ kHz}$	$R_N = -108.0 \text{ dBm}$	$R_N = -108.0 \text{ dBm}$	$R_N = -108.0 \text{ dBm}$
CARRIER MARGIN	$C_m = 8.4 \text{ dB}$	$C_m = 8.1 \text{ dB}$	$C_m = 5.2 \text{ dB}$

Table II.G-3. Telemetry RF Link Carrier Margins¹ versus Antenna Spherical Coverage

PERCENT SPHERICAL COVERAGE	ATM LINKS		AM LINKS		
	FWD DIPOLE	AFT DIPOLE	DISCONE 1	DISCONE 2	LAUNCH STUB
75%	+4.1 dB	+7.8 dB	+8.4 dB	+8.1 dB	+5.2 dB
80%	+2.1 dB	+6.3 dB	+7.2 dB	+6.6 dB	+3.9 dB
85%	-0.2 dB	+4.3 dB	+5.4 dB	+5.4 dB	+2.6 dB
90%	-2.6 dB	+2.1 dB	+2.9 dB	+3.1 dB	+1.1 dB
95%	-5.5 dB	-1.0 dB	-0.1 dB	+0.1 dB	-1.0 dB

1 - CARRIER MARGIN CALCULATED AT HORIZON (1,300 n mi)

Table II.G-4. ATM Command RF Link Calculations

PARAMETERS	FWD ANTENNA LINK	AFT ANTENNA LINK
STDN XMTR POWER (10 KW)	$P_t = 70.0$ dBm	$P_t = 70.0$ dBm
STDN ANTENNA GAIN (LHCP)	$G_t = 18.0$ dB	$G_t = 18.0$ dBm
STDN LOSSES (XMTR CIRCUIT + ANTENNA POINTING LOSS)	$L_x = 1.0$ dB	$L_x = 1.0$ dB
SPACE LOSSES (FREQUENCY = 450 MHz, RANGE = 1,300 n mi)	$L_s = 153.0$ dB	$L_s = 153.0$ dB
S/C ANTENNA GAIN (DIPOLES) FOR 95% COVERAGE (LHCP COVERAGE)	$G_r = -18.0$ dB	$G_r = -16.8$ dB
RECEIVE CIRCUIT LOSSES	$L_r = 4.1$ dB	$L_r = 5.1$ dB
RECEIVED POWER LEVEL	$P_r = -88.1$ dBm	$P_r = -87.9$ dBm
RECEIVER SENSITIVITY	$R_N = -104.0$ dBm	$R_N = -104.0$ dBm
CARRIER MARGIN	$C_m = 15.9$ dB	$C_m = 16.1$ dB

Table II.G-6. Command RF Link Carrier Margins* versus Antenna Spherical Coverage

SPHERICAL COVERAGE (PERCENT)	ATM LINKS		AM DISCONE 1 LINKS		AM DISCONE 2 LINKS		LAUNCH STUB LINKS		CMD STUB LINKS	
	FWD DIPOLE (dB)	AFT DIPOLE (dB)	MOD 33 RCVR (dB)	MOD 27 RCVR (dB)	MOD 33 RCVR (dB)	MOD 27 RCVR (dB)	MOD 33 RCVR (dB)	MOD 27 RCVR (dB)	MOD 33 RCVR (dB)	MOD 27 RCVR (dB)
75	+25.3	+25.2	+23.4	+16.4	+23.7	+17.4	+16.6	+11.1	+19.8	+14.0
80	+24.3	+23.7	+22.2	+15.2	+22.5	+16.2	+15.9	+10.4	+18.3	+12.5
85	+22.6	+22.2	+20.5	+13.5	+20.7	+14.4	+15.2	+9.7	+15.8	+10.0
90	+20.3	+19.7	+18.3	+11.3	+18.5	+12.2	+14.3	+8.8	+13.3	+7.4
95	+15.9	+16.1	+15.0	+8.0	+14.7	+8.4	+13.5	+8.0	+10.0	+4.2

* CARRIER MARGIN CALCULATED AT HORIZON (1,300 n mi)

for each of the ATM and AM antennas. The analysis results were presented in the form of antenna directivity contour plots and cumulative gain plots for each antenna element, and diversity patterns and cumulative gain plots for combined antenna coverage.

The antenna directivity plots presented the relative field strength (i.e., relative to maximum and isotropic) in a specified polarization at any point on an imaginary sphere enclosing the SWS antenna element. The relative field strength (or power level) was identified by an amplitude in decibels at every angle of θ and ϕ . The data for the directivity plots were taken every two degrees in θ and two degrees in ϕ in one decibel increments. Directivity plots were presented for right-hand-circular-polarization (RHCP), left-hand-circular-polarization (LHCP), and both orthogonal linear polarizations for each ATM command and telemetry antenna and for the AM ranging helix antenna; and RHCP and LHCP for the AM command and telemetry antennas.

The COCOA computer program was used to compute the spherical area and associated percentage of the total area for each decibel level on the directivity patterns. Power at each decibel level was then computed and summed to obtain the total power, from which the isotropic level (with respect to the maximum level) was obtained. Specific directivities at any spherical coordinate θ and ϕ would then be referred to this isotropic level.

Based on the above directivity data, graphical analysis was performed to obtain the cumulative percent spherical coverage for all the SWS antenna system patterns (command and telemetry).

Special contour plots were prepared for all the ATM and AM telemetry antennas to reflect the polarization diversity capability of the STDN for telemetry reception. Composite data tapes for the directivity patterns were generated using original RHCP and LHCP data. Complementary data (RHCP and LHCP) for each element, SWS configuration, and telemetry frequency were then compared, data point for data point, at each θ , ϕ look angle recorded on each pattern. The highest absolute directivity level, at each point was recorded on the composite data tape, which was used to generate the combined circular polarization diversity patterns for each of the telemetry antenna combinations. A number of these combinations were analyzed to generate the combined coverage data and the associated cumulative gain curves.

The measured antenna data, described previously, was compared with the specification antenna coverage levels contained in the Skylab to STDN ICD. The comparison was made using the appropriate cumulative gain curves, also mentioned previously. A summary of this information is contained in Tables II.G-7 and II.G-8. For the telemetry antenna, the RHCP and combined RHCP and LHCP data shown for these are compatible with the STDN receiving system. For the command antennas the LHCP data is shown because this is the polarization of the STDN command transmissions.

Table II.G-7. Skylab Telemetry System to STDN Coverage Requirements

TELEMETRY ANTENNA COVERAGE SUMMARY			
ANTENNAS	SPECIFIED COVERAGE(%)	MEASURED COVERAGE	
		RHCP (%)	RHCP+LCHP(%)
ATM DIPOLE (AFT), WING 713	N/S	73 (-6 dBi)	77 (-6 dBi)
ATM DIPOLE (FWD), WING 710	N/S	60.5(-6 dBi)	65 (-6 dBi)
AM LAUNCH STUB, -Y+7 ⁰ (LAUNCH)	0 dBi over 15	28	33
AM LAUNCH STUB, -Y+7 ⁰ (ORBIT)	-5 dBi over 35	49	54
AM DISCONE 1	-5 dBi over 50	70	74
AM DISCONE 2	-5 dBi over 50	64	70
COMPOSITE: ATM DIPOLES	-6 dBi over 97	N/A	97
COMPOSITE: AM DISCONES	-5 dBi over 85	N/A	94.5
COMPOSITE: AM DISCONES + LAUNCH STUB	N/S	N/A	99.1 (-5 dBi)
COMPOSITE: AM DISCONE 1 + LAUNCH STUB	N/S	N/A	87.5 (-5 dBi)
COMPOSITE: AM DISCONE 2 + LAUNCH STUB	N/S	N/A	87.5 (-5 dBi)

N/S = Not specified.
 N/A = Not available.
 dBi = decibel isotropic

Table II.G-8. Skylab Command System to STDN Coverage Requirements

COMMAND ANTENNA COVERAGE SUMMARY		
ANTENNAS	SPECIFIED COVERAGE	SPECIFIED COVERAGE (LHCP %)
ATM DIPOLE (AFT), WING 712	-6 dBi over 82%	68
ATM DIPOLE (FWD), WING 710	-6 dBi over 82%	63
AM COMMAND STUB, -Z-7°(LAUNCH)	-14dBi over 75%	78
AM LAUNCH STUB, -Y+7°(LAUNCH)	N/S	74.5 (-14 dBi)
AM COMMAND STUB, -Z-7° (ORBIT)	-14dBi over 80%	83
AM LAUNCH STUB, -Y+7° (ORBIT)	N/S	80 (-14 dBi)
AM DISCONE 1	-14dBi over 90%	93
AM DISCONE 2	-14dBi over 90%	92
COMPOSITE: ATM DIPOLES	-6 dBi over 95%	98
COMPOSITE: AM DISCONES	-14dBi over 97	99.8
COMPOSITE: AM DISCONES + COMMAND STUB	-14dBi over 98	99.9
COMPOSITE: AM COMMAND + LAUNCH STUBS	N/S	99.9 (-14 dBi)
COMPOSITE: AM DISCONE 1 + COMMAND + LAUNCH STUBS	N/S	99.9 (-14 dBi)
COMPOSITE AM DISCONE 2 + COMMAND + LAUNCH STUBS	N/S	99.9 (-14 dBi)

N/S = Not specified.
dBi = decibel isotropic

(c) RF Beat Frequency Analysis. The problem of interaction of RF signals generated on board Skylab was evaluated under a computerized beat frequency analysis implemented early in the program. The primary responsibility for this task was given to the EMC Subpanel. Through this medium, a beat frequency analysis plan was generated and data coordination between the two centers was maintained. The analysis evaluated the interaction of all RF frequencies (including experiments) that could cause problems onboard Skylab. The effects of intermodulation products, harmonics, and image frequencies were identified and their impact on system operations evaluated. Those frequencies that were identified as potential problems were resolved by vendor qualification tests or module/module tests.

(2) Data Systems Analysis. Because the ATM and AM data systems were designed on previous programs, the analysis for design verification were confined primarily to the compatibility of the data system as it interfaced with the RF transmitters and antenna.

In particular, the evolution and changes to the AM transmitters were based on the need for adequate RF signal margin, data modulation bandwidth requirements and corona. The use of two 2 watt transmitters in the AM (selected in part to prevent corona and no cooling during launch and storage) gave way to the selection of one 2-watt transmitter and three 10 watt transmitters (similar to the ATM transmitters) based on analyses of insufficient circuit margin, redundancy, and possible degradation in equipment performance as the mission duration was increased. Analysis had indicated that the transmitter used during launch could operate without any coolant and be corona free if the power output was maintained at less than 2 watts. In the final configuration, a 2 watt transmitter was installed for launch purposes (and as a back-up during flight) while three 10 watt transmitters were provided for on-orbit operations to support real-time PCM, delay-time PCM, and delay-time voice transmission simultaneously.

(3) Command System. Because the ATM and AM command systems were developed on previous programs, the primary analyses were conducted in the area of reliability and ground-to-air link analyses.

Compared to Skylab both the ATM and AM command receiver/decoders were qualified for short duration missions. As the mission duration became longer (greater than 56 days) the requirements for redundancy in the ATM command system was addressed. When the Skylab program changed in concept from the WWS to the DWS in July 1969 and the subsequent decision for the ATM attitude control system to be responsible for the total cluster control, the ATM command system was reviewed in light of its interface with the ATM digital computer. The result was to provide a parallel redundant system, (command antenna, receiver, and decoder) capable of operating in active redundancy or each parallel half operating by itself.

(4) Ranging System Analysis. Design analyses for the VHF ranging system were primarily in the type of antenna required on the SWS and its location. Influencing parameters included the SWS orientation during rendezvous. The original antenna evaluated was a Gemini type stub antenna mounted on an AM truss; however, as the SWS orientation for rendezvous became firm, the need for a helical antenna with various beam widths was analyzed. In addition, circuit margin analyses were conducted with the antenna located on an AM boom, the MDA, and on the ATM truss. These analyses led to a 5-turn helix with a 3 dB beamwidth of 50 degrees and a 9 dB gain mounted on the ATM truss and pointed along with the X axis of the SWS, capable of operating at a maximum range of 300 n mi. Another analysis included the tracking capabilities for rendezvous function for terminal phase initiations (TPI) maneuvers for ranges less than 30 n mi. The loss of tracking data for certain approach angles were identified.

(5) Audio System Analysis. Design analyses of the audio system was divided in two areas; system analysis and hardware analysis.

Systems analysis consisted of identifying the support functions required of the audio system and the types of controls, displays, and facilities required by the crew. These analyses and requirements were maintained and updated via the Audio Systems Requirements document, which was continually revised by meeting with crew systems organizations and technical organizations from MSFC, JSC, and their contractors. An audio working group was formed to evaluate crew requirements, experiment requirements, and the overall mission requirements. The outputs were defined in terms of what type functions, displays, and controls would be required of the hardware. Hardware analyses included:

- Modifications to the lightweight headset to increase microphone signal output and reduce loading on the microphone bus when multiple headsets were on one channel.
- Channel-to-channel crosstalk analysis due to the earphone line of both channels connected to a common C&W system.
- Systems gain analysis for the normal and rescue configuration based on variation in the crewmans voice and off-nominal head-to-microphone position.

(6) Television System Analysis. A detail analysis was conducted on the Skylab TV system to evaluate the quality of TV pictures as monitored on the ground. Analyses were conducted on the airborne system to assure that the quality of the signal being sent from the Skylab was sufficient to yield a good picture. Such parameters as frequency response, coaxial cable attenuation, linearity, video bus levels, and the RF link were considered. Also considered, was the effect of the SWS/CSM accumulated tolerances on the video signal level.

The results of this analysis led to the conclusion that the signal-to-noise of the video signal would be at least 30 dB, based on the carrier-to-noise ratio as predicted by the RF link analysis. It was determined that the linearity of the system was satisfactory and the bandwidth of the downlink signal would be limited by the CSM transmitter.

Other analyses included:

- System grounding to eliminate a shock hazard in the portable TV camera.
- Coaxial cable shield grounding through the MDA video switch.

b. Tests. Testing of the data systems included obtaining data on antenna patterns, compatibility tests with STDN ground stations, corona tests, and transmitter operation without cooling. The need for major test programs and plans were evaluated and directed by means of the I&C panel meetings. Where applicable these requirements were assigned to subpanels or ad hoc working groups. In particular, scale model antenna testing, EMC tests, GSFC tests, Skylab Test Unit (STU)-STDN tests, MDA/AM attitude tests, and KSC test plans were thoroughly evaluated by the I&C panel. The panel also evaluated the need for simulators at MSFC, JSC, GSFC, or at the module contractors to provide proper equipment and interface compatibility. The panel thus provided complete visibility on what was being tested so duplicate tests would not be performed. The panel also was a center for dissemination of test data.

The need for the panel to develop overall test philosophies was to a large degree based on to what extent and where the Skylab modules could be mechanically interconnected as a cluster to substantiate the I&C systems, especially in the areas of ground loops, EMC, RF beat frequencies, and acoustics. When considering the overall cost of some of these plans, it became apparent that a total interconnected Skylab could not be tested as a unit and intermodule testing would have to suffice.

Because portions of the Data and Communication system were located in every module of the SWS, considerable intermodule tests were required to verify system integrity. For example, separate interface tests were conducted between the MDA/AM and the CSM and the MDA/AM and the OWS for the audio and TV system due to facility limitations. For the same reason, the ATM television subsystem was never ground tested with the CSM RF subsystem. To compensate for the lack of a total end-to-end tests, special test equipment and simulators were required to facilitate intermodule tests. In addition to module/intermodule tests compatibility tests were required at the various NASA centers and contractor sites to evaluate hardware interfaces in a timely manner. These included antenna pattern tests, audio, TV, and air-ground communication interfaces.

(1) Antenna Tests. The need for antenna tests was recognized early in the Skylab program. Tests, using scale model antennas,

were identified for the CSM, ATM, and AM to verify antenna location, radiation patterns, spacecraft shadow effects and define regions of acceptable spacecraft look angle.

Scale model of the CSM, AM, OWS, and ATM were provided so measurements could be made in the launch and orbital configuration. Polar plots were obtained at various locations to determine a satisfactory location for the stub antennas.

As the cluster configuration became modified by the addition of the OWS solar panels, two UHF discone antennas were designed and located 90 degrees apart on extendable booms.

Antenna measurements were performed and principal plane radiation pattern polar plots obtained to allow selection of a satisfactory location within the constraints of the cluster geometry.

(2) STDN Compatibility Tests. The STDN/SWS compatibility tests were conducted at GSFC, JSC, and MDAC-E. A typical STDN ground station was located at each site. Testing at GSFC addressed nominal compatibility of the AM and ATM Data Systems and the AM and ATM command systems with STDN. The GSFC tests are itemized in Table II.G-9. These tests consisted of sending AM/ATM PCM data tapes to GSFC for playback through their ground station. Conversely, GSFC-generated command tapes were verified with the ATM and AM command systems.

The one significant problem during the GSFC tests was the loss of synchronization by the ground station during playback of AM subframes 3 and 4 and M509 PCM data. The problem was resolved by all STDN sites dedicated to Skylab to have a Model 317A Monitor Bit Synchronizer installed and operating before the launch of SL-1/2.

Other STDN interface tests were conducted at JSC to determine the compatibility of the TV and Audio System that used the CSM S-Band system for communication with the ground. No problems were encountered with audio downlink or uplink. Significant results of TV tests included:

- Verification of signal level at the MDA/CSM interface for optimum modulation index of the CSM transmitter.
- Because the ATM camera pictures an aspect ratio of 1:1 JSC was prepared to provide an optical converter for conversion to a commercial aspect ratio of 4:3 when the ATM picture was provided for network distribution.
- In the course of these tests, it was found that the color camera video-to-sync signal ratio was 100:28 as compared to the standard commercial ratio of

Table II.G-9. GSFC Compatibility Tests

TEST	PROBLEMS IDENTIFIED
ATM TM TRANSMITTER SERIAL BIT ERROR RATE VS TOTAL RECEIVED POWER	NONE
AM TM TRANSMITTER SERIAL BIT ERROR RATE VS TOTAL RECEIVED POWER	NONE
ATM TM TRANSMITTER REAL TIME AND DELAY TIME FORMAT DECOMMUTATION AND DATA TRANSFER.	NONE
AM TM TRANSMITTER REAL TIME AND DELAY TIME FORMAT DECOMMUTATION AND DATA TRANSFER	NONE
ATM TAPE RECORDER	M509, SF 3, & SF 4 SYNC LOCK. MSFTP-II FORMAT SUSCEPTIBLE TO BOTH PRERECORDED AND SIMULATED DATA.
AM TAPE RECORDER	
COMBINED AM/ATM PCM TELEMETRY	NONE
AM AND ATM COMMAND SYSTEMS/STDN STATION COMPATIBILITY	NONE
AM DCS/TELEPRINTER/TM/ELECTRONIC TIMER/STDN COMPATIBILITY	NONE
COMBINED ATM DCS/REAL TIME PCM SYSTEM/MEMORY LOAD UNIT/DIGITAL COMPUTER/STDN COMPATIBILITY	NONE

100:40. This required modification to the VTR and TV GSE as used for KSC checkout.

- Playback of the interleaved audio and video from the audio splitter disclosed a 60 Hz hum on the voice signal. This was found to be due to the VTR sync tip damping circuit that was damping at a different level when the Pulse Amplitude Modulation (PAM) voice signal was interleaved with the video. The VTRs were returned to Radio Corporation of America (RCA) from KSC for a circuit modification to correct this problem.

(3) STU-STDN Facility. Approximately one year before launch of SL-1, work began at MDAC-E to establish a single test facility where the major elements of the Skylab Data and Communication hardware and STDN ground equipment would be simulated. The purpose of the facility was to

(a) perform compatibility testing of the Skylab Audio, TV, Command and Telemetry Systems, and

(b) provide mission support.

Simulation of the Skylab system also included the CSM audio and RF systems and the ATM telemetry system.

The system was used to support the audio and TV system tests during the AM/MDA 5 psia altitude chamber tests; assist in resolving the ground synchronization problem associated with the AM data playback, and conducted limited AM PCM waveform testing. Off-nominal TV testing was also conducted to provide background data in anticipation of possible mission problems.

(4) Data System Tests. The primary test verification on the AM and ATM data systems was in the area of corona and tape recorder life tests.

(a) Corona Test. The pressure profile that the AM RF equipment would be required to operate during launch was found to be affected by the OWS IU venting of water vapor. Corona versus altitude pressure tests were conducted to determine the probability of corona occurrence and possible equipment damage. Comparison of the equipment test data and the expected pressure profile indicated adequate safety margin and/or no equipment damage should corona occur for the 10 watt transmitter, coaxial switch and the quadriplexer. However a constraint was established in that the transmitter power must be removed before the cycling of the coaxial switch from the launch of SL-1 plus 24 hours.

Power-altitude tests on the quadriplexer showed corona could occur at 2.5 watts and at pressures greater than 1.56×10^{-2} mm (Hg). This resulted in a recommendation that the power from the 2 watt transmitter be limited to 2 watts or less.

However, this design limitation was modified when corona was experienced during the altitude chamber test simulating the operation of the 2 watt transmitter during the boost phase of the SL-1. It was subsequently determined that corona was affected by the Voltage Standing Wave Ratio (VSWR) and phase angle. Rather than modify the quadriplexer, additional attenuation was inserted, limiting the quadriplexer input power to 1.8 watts. During the course of these tests, it was also determined that commands could be sent through the quadriplexer even if corona should occur at another port.

(b) Tape Recorder Life Test

1 AM Recorder Extended Life Test. An extended life test program was implemented and successfully completed on 3 AM tape recorders in March 1973. Test parameters included, bit error tests, end-of-tape, start of tape cycling for 3 temperature environments (plus 4.5 degree centigrade, ambient, and plus 49 degree centigrade) and record/playback cycling tests ranging from 240 to 860 hours at ambient temperature. Although a failure did occur during these tests, the cause was found to be a motor bearing that was not lubricated during manufacture. A traceability check was made and three tape recorders had bearings replaced.

2 ATM Tape Recorder Test. On December 28, 1972 a life test failure occurred on the ATM tape recorder. The recorder had completed 120 days of the 266-day life test. Failure was due to the recorder throwing tape loops, which caused the motor to stall. Tape loops occur particularly when the tape reel must decelerate at the end-of-tape, stop and then reverse directions. Because a short strip of tape at each end has the oxide material removed, this allows a light (which is directed at the tape) to shine through this "window" and activate a detector circuit that causes the machine to stop and reverse its direction. The throwing of tape loops was found to be associated with the difference in friction between the tape that has oxide material removed and the rest of the tape together with temperature and humidity. The higher the temperature, the greater the tendency to throw tape loops; therefore, the upper limit of the tape recorder temperature was reduced from +40°C to +30°C and it was decided that the failure on December 28, 1973 on the nonflight life test unit did not warrant the need for any flight unit modification. The recorder subsequently completed its life test with no additional failures.

(5) Command System Test. Verification tests on the command system were incorporated as a part of the STDN compatibility tests, antenna pattern tests, and corona tests. In addition, tests were conducted for interference to command receptions of Digital Command System (DCS) receiver/decoders due to possible mixing of the three AM transmitter frequencies within the quadriplexer. Test results verified proper reception of commands through the quadriplexer while the three transmitters were operating, with and without modulation.

(6) Ranging System Test. To validate the SWS antenna/transponder design the ranging system was tested for the following parameters:

- Receiver Sensitivity
- System Delay
- Jitter
- Sync-Slip Test
- Acquisition Capability
- Automatic Gain Control (AGC) Voltage Calibration

In addition, radiation distribution plots on the 1/20 scale model of the SWS were made to evaluate the antenna coverage.

5. Conclusions and Recommendations

a. Conclusions. The I&C system performed as expected for the entire mission. All equipment failures were protected by system redundancy design, onboard spares for replacement, or alternative operating techniques. Some data channels were lost or degraded during the mission, but in all cases the user had sufficient other data to monitor and analyze the systems operation. The Skylab program proved that both repair and replacement activities can be conducted on electronic equipment.

Designing I&C equipment and installations for inflight maintenance should be a prime consideration for all future manned space flight programs.

b. Recommendations. These recommendations are directed toward the system implementation of the various portions of the I&C system on future missions. In the establishment of future systems, all requirements and ICDs should be completely aired, reviewed, and concurred in by all interested parties early in the program to minimize configuration changes. Systems and equipment requiring frequent personal use should undergo a thorough dry run so all desired operating conditions are explored and any constraints engineered out of the systems.

(1) Data Systems. On future missions comparable in time and experiment complement to Skylab, data systems should be more flexible in format and incorporate capabilities such as data compression, priority program selection, and system redundancy for every measurement.

Permission marriage testing of the flight and operational ground data systems should be conducted in all possible modes.

(2) Command System-Timing System. A method should be incorporated to update any timing signals generated by vehicle systems. Use of the timing update to maintain a common time between the flight vehicle and the ground should minimize the problem of correlation between ground and airborne data of related observations and events. When multiple vehicles are joined, a single time reference system should be used.

(3) Audio System. Future manned programs with large operational volumes and/or separate compartments should consider the use of portable low-sensitivity wireless microphones. These would permit a crewman to talk into an intercommunication system from anywhere. The crewman could receive calls and responses from speakers located throughout the vehicle.

Hearing aids should be considered for crewmen's use during habitation of low-pressure environments. These devices will compensate for the drop in acoustical efficiency of the atmospheric medium and in effect will allow loud speaker volumes to be reduced to a lower level and enable some voice conversations to take place without the aid of intercom systems.

(4) Television. Minor additions to components to provide easier use by the crew are the recommendations for the TV system.

When more than one camera is included in a mission, an identification code should be included in the vertical interval test signals. The addition of a lens with a wider angle of view than that available on Skylab appears useful for confined interior scenes.

Effective use of the tape recorder would be heightened by the addition of a digital "tape remaining" indication on the recorder, an "end-of-tape" signal that could be presented visually and audibly throughout the vehicle, and the remote control of tape moving and tape stop from positions throughout the vehicle where the camera is operated.

(5) RF System. Externally-mounted RF equipment with voltage levels that could experience corona should be located so it will not be exposed to any venting from the vehicle. Venting during the Skylab EVAs is strongly suspected of causing local partial pressures in the area of vented RF equipment sufficient to cause equipment malfunction or failure.

H. ATM Control and Display Subsystem

The ATM C&D subsystem provided the first attempt to integrate the command and control functions of a group of related scientific instruments. Six primary solar experiments, their supplemental pointing aids and experiment support subsystems were controlled and monitored by on-orbit astronauts through the use of the C&D subsystem. The subsystem consisted of four major assemblies: the C&D console, the inverter lighting control assembly (I-LCA), the rotation control panel (RCP), and the digital address system (DAS) backup panel. Together, these assemblies provided the man-machine interface that allowed the astronauts to conduct the solar experiments, make manual adjustments to the Skylab attitude, control experiment pointing, install and retrieve film canisters, regulate power, perform housekeeping functions, control lighting, and monitor both consumables and potential trouble spots.

1. Functional Description. The ATM C&D Subsystem is shown in Figure II.H-1. Conditioned power for the console was provided by the I-LCA. Backup source for this power was provided by the Backup Inverter Lighting Control Assembly (BI-LCA). The crew interface was provided primarily by the ATM C&D Console which provided the controls and displays required to operate the ATM experiments and subsystems. Commands were provided to the ATM by toggle and rotary switches, the Manual Pointing Controller (MPC) and the DAS. Monitoring was accomplished by the use of status lights and flags, alert lights, dual-scale vertical meters, pulse counters, digital displays, activity history plotter, and TV displays. Additionally, the C&D Console interfaced with the MDA Radio Noise Burst Monitor (RNBM), provided data recording and monitoring capabilities and, with the OWS TACS, provided status monitoring and thruster inhibit command capabilities. All critical command and display functions were implemented through redundant wiring and switching contacts and alternate displays, or were available through the DAS. The I-LCA, BI-LCA, the DAS backup device, and the RCP were powered through the console power distribution networks. Power was provided from redundant ATM +28 Vdc buses to the console and was routed via circuit breakers or switch contacts to the subsystem components. The I-LCA was energized from redundant console buses, derived directly from ATM buses, and overload protected by a pair of console main circuit breakers. The I-LCA or the BI-LCA were controlled from the console and generated the 400 Hz power and the 5 Vdc power required by the console displays. Circuit breakers at the console, provided overload protection to the fixed 400 Hz buses and to the fixed, unregulated +5 Vdc buses. Current limited outputs were incorporated in the design of the variable and fixed, regulated +5 Vdc supplies. The unregulated +5 Vdc output lines were fused in the I-LCA. The DAS backup device was normally off-line, allowing commands to be entered to the ATM switch selectors and ATMDC from the console DAS. Although it was never required during the mission,

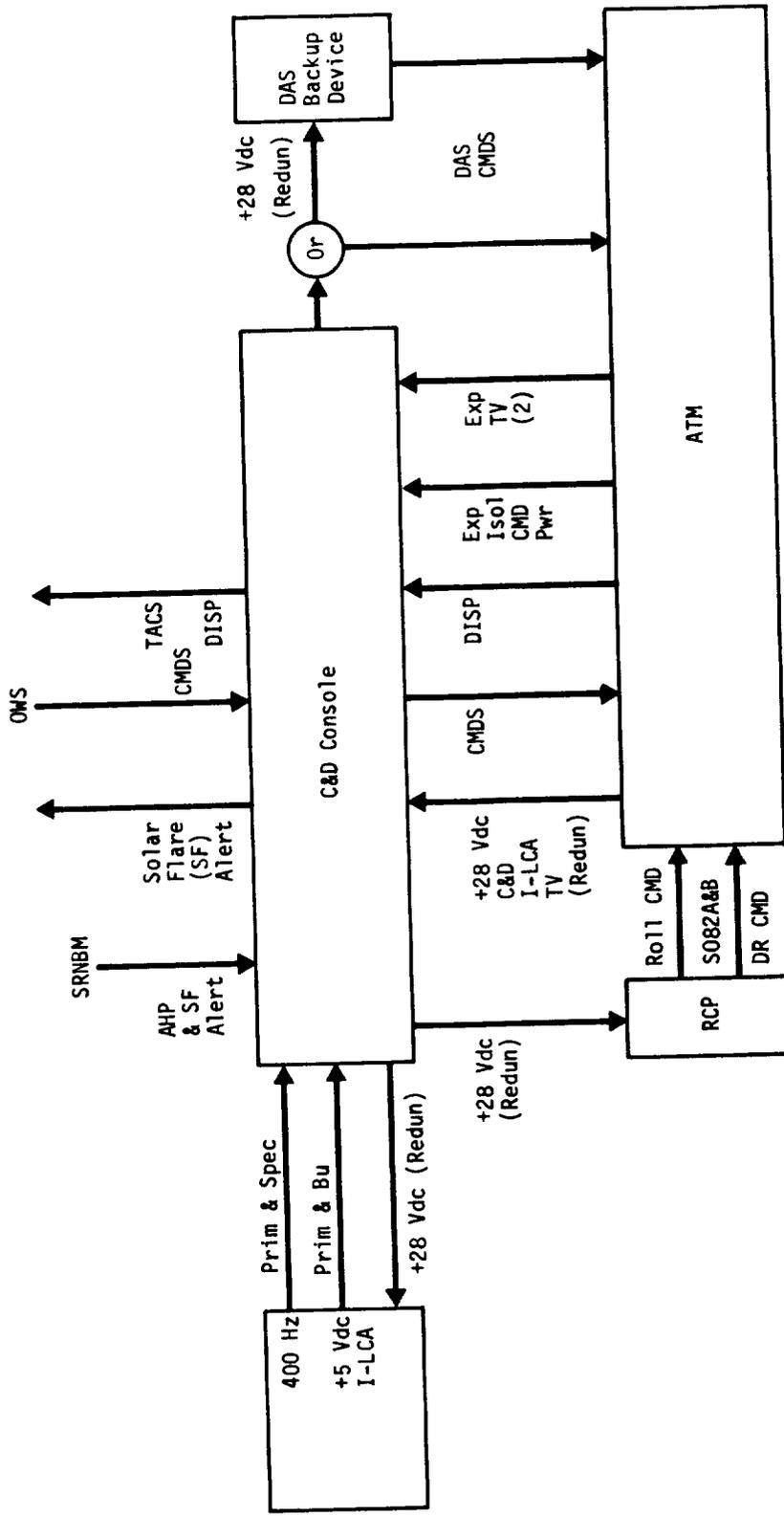


Figure II.H-1 ATM C&D Subsystem Block Diagram

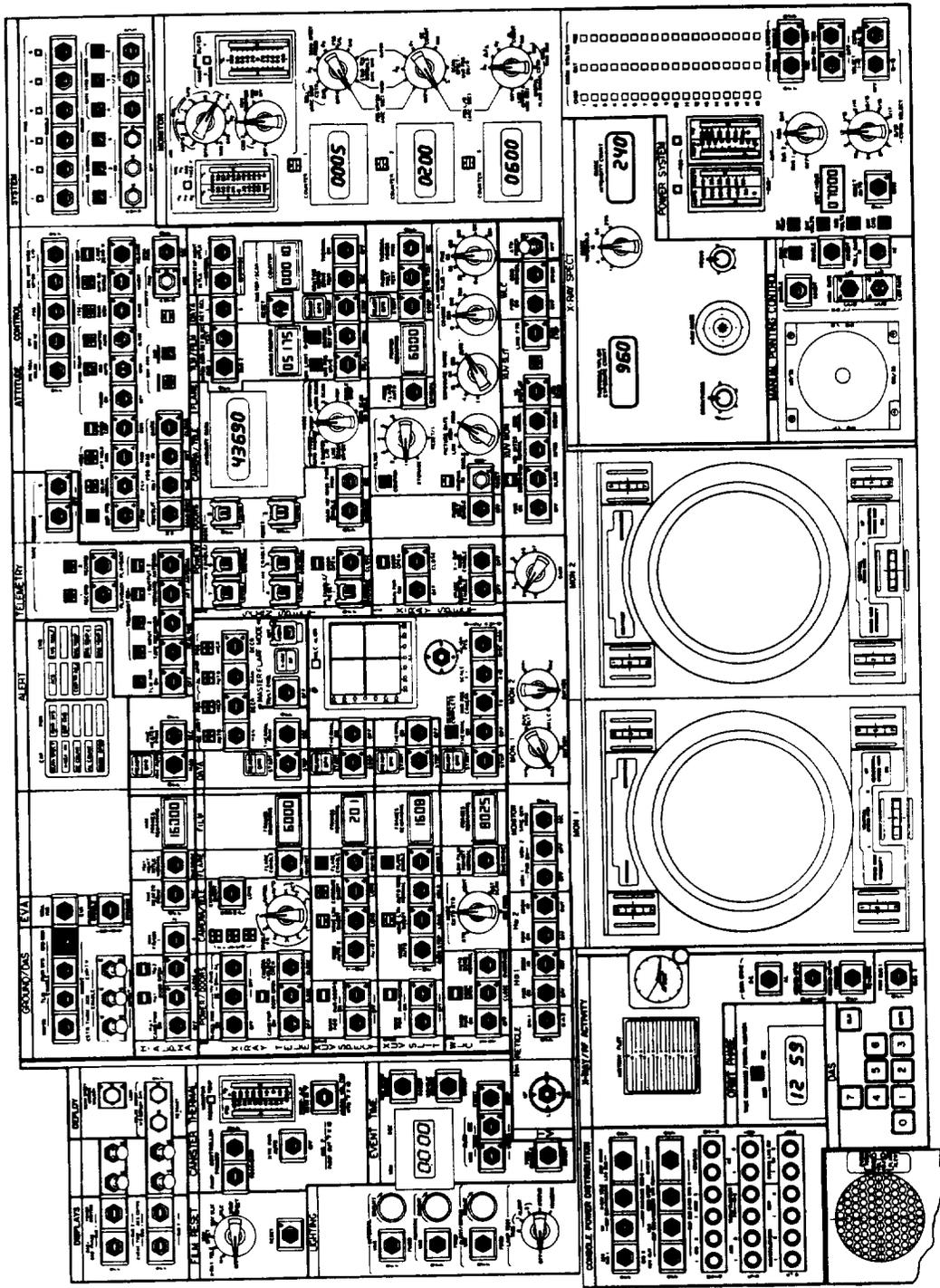
the device was designed so the console DAS outputs would be open circuited and ATM commands manually entered via the backup device. The RCP was enabled from the console during ATM EVA activities by a switch closure. When enabled, ATM canister rotation and S082 A&B experiment doors commands were provided by the RCP under control of the EVA crewman.

2. Control and Display Console. The console panel layout is shown in Figure II.H-2. The general arrangement provided for experiment controls to be centrally located with associated subsystem controls placed around its periphery. The upper console contained the main experiment controls in a matrix arrangement. Controls for experiments that were activated in a general time sequence ran from left to right in two main groups with common control functions aligned in columns. This allowed quick activation of experiment power, opening of doors, selection of camera modes, etc. All TV controls were located immediately below the experiment matrix and above the TV monitors. The lower console contained other experiment-related functions such as the TV monitors, X-ray scope, X-ray activity plotter, and manual pointing control stick. The control stick was positioned for right-hand operation for all the ATM astronauts were right-handed.

The remainder of the console was taken up with associated subsystem controls. The TM and pointing control system (PCS) controls were located at the upper right; the CMGs control and monitor equipment along the right side; power systems controls at the lower right, and the digital keyboard and panel circuit breakers were located in the lower left. Along the left-hand side of the console were the panel lighting controls, an event timer for use with experiments, thermal controls for the telescope canister, and a film reset knob. Explosive devices controls were located in the upper left-hand corner. The upper left contained switches to enable or inhibit ground control, and the upper center was used for alert readouts.

a. Design Requirements. The philosophy incorporated in the ATM C&D Console design is summarized as follows:

- LM concept was used where practical.
- Maximum use of LM and CM flight-qualified hardware was used.
- Operation by either one or two crewmembers in a shirtsleeve environment was provided.
- The console was capable to operate continuously while the cabin was pressurized.



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Figure II.H-2 ATM Controls and Display Console Layout

- Design, location, and use of all controls and displays were in accordance with standard human engineering practices, where practical.
- Redundant circuitry and circuit protection were incorporated to eliminate the possibility of loss of parts of more than one experiment, or loss of an entire experiment or subsystem due to a single point failure.
- No scheduled maintenance was planned during flight.

The basic structural envelope of the ATM C&D Console was a carry-over configuration from the WWS phase of the Skylab program. As originally conceived the ATM C&D Console would be installed and operated in the LM. Due to the severe space limitation in the LM, a somewhat unorthodox console configuration evolved. Console cutouts and dimension limitations (particularly in depth) were designed to satisfy the LM requirements.

The DWS concept eliminated using the LM and the ATM because part of the DWS cluster. The ATM C&D Console, as a result, was relocated in the MDA. Although the MDA location provided a more spacious location, design considerations at this point in the program required that the C&D Console remain basically as conceived for the LM. Relocation of the console into the MDA, however, necessitated a new structural interface definition. The dynamic environment in the MDA was more severe than in the LM, thus creating increased concern in the ability of the C&D components to survive the vibration. To counteract this, a four point, vibration-isolation mounting scheme for the entire console was devised that placed the console center-of-gravity in the plane of four symmetrically located isolators.

b. ATM C&D Console Functional Description. The ATM C&D Console contained all components required for commanding and monitoring the following ATM experiments and subsystems:

- Experiments
 - Hydrogen-Alpha (H-~~α~~) 1 and 2 telescopes
 - X-Ray Telescope (S056)
 - Extreme Ultra Violet (XUV) Spectroheliograph (S082A) and Spectrograph (S082B)
 - White Light Coronagraph (WLC) (S052)
 - Ultra Violet (UV) Scanning Polychromator Spectroheliometer (S055A)
 - X-Ray Spectrographic Telescope (S054)

- Subsystems

Attitude Control System (ACS)

Telemetry

Power System

TV System

Canister Thermal

Ground/DAS

Alert

The ATM C&D components were arranged on nine panel assemblies, with the experiment controls and displays centrally located in a row-column matrix configuration where rows across contained experiment controls and displays and columns down contained controls and displays having a common function. Subsystem controls and displays were functionally grouped around the periphery areas.

A History Event Recorder, located in the lower left-hand corner of the console, was designed to provide an onboard record of solar activity. The device allowed simultaneous recording of two channels of analog data. One channel recorded the X-Ray Telescope (S056) X-Ray Event Analyzer (X-REA) outputs. The other channel recorded RF activity as provided by the Solar RNBM. These data were recorded on five cycle logarithmic paper at a selected paper rate of either 10 inches per hour or 30 inches per hour. The paper could also be run in a review mode at 1,800 inches per hour in the forward or reverse directions. Time reference was recorded, via a third channel, in Greenwich Mean Time provided by the ATMDC in hours, minutes, and seconds. Due to a preflight test mishap and an onorbit procedure error, the plotter became jammed and inoperative during SL-2.

The ACS controls and displays provided: activation and mode selection of the Experiment Pointing Control Subsystem (EPCS), Star Tracker, and Momentum Dump; override controls for the CMG subsystem and the ATMDC; TACS inhibit commands and thruster status, and Fine Sun Sensor (FSS) experiment bias enter controls. The Monitor area of the C&D panel provided for the display of ACS parameters (and selected experiment data) on two dual scale vertical meters and three numeric displays. Critical ACS parameters were redundantly wired and displayed. The MPC provided up/down, right/left manual control of the Experiment Pointing System (EPS) and Star Tracker inter/outer gimbal positioning. The MPC could be replaced in orbit with a spare provided in onboard storage. The replacement was not required.

The TM System controls and displays provided for activation of the system and mode control. Mode controls allowed the activation of the ATM tape recorders in the record or playback mode, the selection of tape recorder or real-time inputs to the ATM transmitters, and the selection of forward or aft antennas for each transmitter.

The Power System Displays provided status monitors for the individual ATM CBRMs, status flags that cued the operator to off-nominal conditions, and dual scale vertical meters used to monitor parameters of the ATM main buses and individual CBRMs. Controls were provided to activate all CBRMs simultaneously or to turn ON/OFF individual chargers and regulators. An ATM Power Off switch, bordered in red, was provided to permit rapid deactivation of the ATM.

The TV controls provided for the activation of the ATM TV system and for the operation of the individual experiment TV cameras. Two TV monitors were provided, each of which could display any of five TV signals from ATM experiments H α -1, H α -2, XUV Monitor (MON), WLC, and XUV slit. The monitors allowed the operator to point the instruments at a particular area of interest and to determine the FSS biases required to compensate for FSS misalignment with instruments having fine pointing requirements.

The TV monitors received noncomposite video signals. External horizontal and vertical drive signals were supplied from the ATM synch generator. Capability was provided to display and control electronic cross-hairs. The monitors had five independent controls for brightness, intensity, and cross hair position left/right and up/down. One of the TV monitors failed at the conclusion of SL-3 (all experiment functions completed) and was successfully replaced at the beginning of SL-4.

The Canister Thermal controls allowed selection of primary/off/secondary pumps and controllers and heater power auto/off. A dual scale vertical meter was provided for display of system parameters.

The DAS keyboard provided the command and data entry capability for functions that had not been allocated a dedicated control and provided the backup command capability for control of critical subsystem functions. Commands were entered in the ATMDC and via switch selectors to the TM, Power, Canister Thermal, Attitude Control, and Experiment/TV ATM systems. The DAS keyboard consisted of eight push-buttons numbered 0 through 7, and an Enter and a Clear pushbutton. When a five digit octal command was typed into the keyboard, the binary equivalent was sent out and accepted by one of the five units associated with the DAS, four switch selectors, and the ATMDC.

The Alert advisory indicators warned the astronaut of a low level malfunction of an ATM experiment or subsystem. The system was independent of the Cluster Caution and Warning (C&W) System and the

functions monitored did not require immediate crew attention. The Alert indicators were energized by ground return with all logic and switching provided by the ATM.

A distributor assembly, which was located at the bottom of the console, accommodated interpanel and subassembly wiring. All panel connections were routed directly to the distributor or interface connectors by means of an interconnecting harness, which eliminated interpanel connector interfaces. Power distribution signal conditioning, and relay switching that was required by the panels was provided by the distributor.

The use of the power distribution switches or circuit breakers provided a flexible power distribution scheme. Console single point failures were capable of being isolated to insure against the loss of an entire experiment or subsystem. Electroluminescent Lighting (EL) was used for panel nomenclature, for integrally illuminated displays, and for numeric readouts. The integral lighting system included panel lamps and the following displays: Vertical Meters, Flags, Cross Pointer, and History Plotter. The integral lighting was considered good by Skylab operating crews. During the SL-4 mission a short developed resulting in the loss of illumination to the displays and nomenclature.

The console design incorporated many components that had flown in space programs before Skylab and were qualified for use in the console as off-the-shelf design items. The majority of these components were qualified for the LM. Relocation of the console in the MDA necessitated new interface definition. The dynamic environment in the MDA was more severe than in the LM, thus creating increased concern in the ability of the C&D components to survive the vibration. The three basic vibration isolation methods considered were: (1) individual isolation of sensitive components, (2) individual isolation of the nine C&D panel assemblies, and (3) vibration isolation of the entire console. The latter method was selected because of severe behind-the-panel space constraints associated with the other two options. A four-point, vibration-isolation mounting scheme was adopted with the console CG in the plane of the isolators and equidistant to the isolators in that plane. The vibration isolators were sized and found to be compatible with existing MDA space limitations. The vibration isolation subsystem, which had a natural frequency of 8 to 12 Hz, provided a compatible environment for the hardware that was previously qualified to LM levels and, thus, requalification at the component level was not required. All components performed satisfactorily without degradation, following exposure to environments during the console qualification test program.

Thermal control was provided by a liquid coolant loop that was designed to meet the following requirements:

- Local panel temperatures not to exceed 105°F.
- Maximum pressure drop of 3.0 psi at 220 lbm/hr.

The coolant loop was an open-cycle, cold-rail system, fluid being supplied externally by the AM coolant system. Cold rails were structurally integrated, using dip brazing techniques for improved thermal conduction to the console structure. The console structure (frame) served as an intermediate heat sink, transferring component heat loads to the coolant loop for removal from the console.

3. Inverter-Lighting Control Assembly Functional Description.
The I-LCA provided regulated and unregulated electrical power, both ac and dc, to the ATM C&D Console. These various types of power were required for the operation of the console display components and the EL of the console nomenclature and display components.

The I-LCA was located externally on the forward conical section of the MDA on the L-Band antenna truss. Operational power was provided to the unit by ATM power buses with input and output circuit breakers located on the ATM C&D console.

The design approach selected to satisfy the significant requirements of a remotely variable output and high efficiency for the ac outputs was the Pulse Width Modulator (PWM) technique. One fixed output and two variable output inverters were operated from 28V bus No. 1, and one fixed inverter capable of supplying the total load was operated from 28V bus No. 2. This approach provided redundancy to protect against single failures. These inverters would automatically shut-down in the case of a short on the output. Circuit protection was provided to prevent over-voltage outputs.

The regulated dc outputs were generated from a ripple preregulator that provided the power to three separate regulator circuits. Two of these were remotely variable from the ATM C&D console. All three were switched to an unregulated backup generated from the fixed PWM inverters.

The I-LCA thermal control was accomplished by a combination of active heaters, selected case finish, and thermal isolators.

A failure occurred on SL-3 resulting in loss of the variable inverter outputs. The remainder of the mission was completed operating the EL from the bus No. 2 fixed inverter. The source of the failure was not isolated and could have been internal to the I-LCA, the C&D console, or the interconnecting wiring.

A BI-LCA system was also provided. The "black box" components of this system consisted of two inverters, two converters, internal and numeric lighting brightness control panels, a connector panel,

and a patch plug stowage panel. These components were located internally in the MDA. Use of the BI-LCA could be acquired by patch plugs. The patch plugs would remove power from the primary I-LCA and completely isolate its circuits. The BI-LCA was not used during the mission.

4. EVA Rotation Control Panel. The EVA RCP (Figure II.H-3), located at the ATM Center Workstation, was used to rotate or roll the ATM experiment canister to any desired position within a range of +120 degrees from a mechanical zero roll reference position. During EVA it served as a control panel to position the ATM experiment canister so each of the four film retrieval/replacement doors (S052, S054, S056 and H-alpha) of the ATM could be aligned with the Center Workstation and ATM experiment film camera assemblies replaced. The EVA RCP contained controls to open the S082A and S082B thermal shield doors at the Sunend Workstation to enable replacement of the S082A and S082B film camera assemblies.

Full rotation control capability existed at the ATM controls and displays console and provided an additional backup to the RCP. Thus, should the RCP control handle become completely disabled ATM film retrieval could be accomplished by controlling canister rotation from the console under the direction of the EVA astronaut.

5. Backup DAS Device Functional Description. The addition of functions addressable only by the DAS required a redundant command capability. The DAS backup device (Figure II.H-4) was added to the C&D subsystem and installed in the MDA adjacent to the right of the console to provide command redundancy. In normal operations the unit was electrically disconnected from the system allowing the console DAS to provide commands.

The DAS backup device was a manual switching unit that used rotary switches to format each command. Digit 1 provides the enable command to the selected ATM switch selector or digital computer, and digits 2 through 5 provide the digitally encoded 12 address data bits. The unit was not needed during the mission.

6. Conclusions and Recommendations. Generally, the ATM C&D subsystem operated well during the Skylab mission. All ATM mission objectives were met and the controls and displays contributed to smooth astronaut performance.

The major crew comments directed at C&D Console design concerned the high density of switches and a preference of rotary switches over the three-position toggle switches. Recommendations from the flight crews were to remove selected switches that were seldom or never used from the panel and group them on a separate panel or incorporate them in DAS. The rotary switches were preferred for ease of verifying switch position during panel scan. The toggle switch positions were not easily identifiable due to the short throw mechanism.

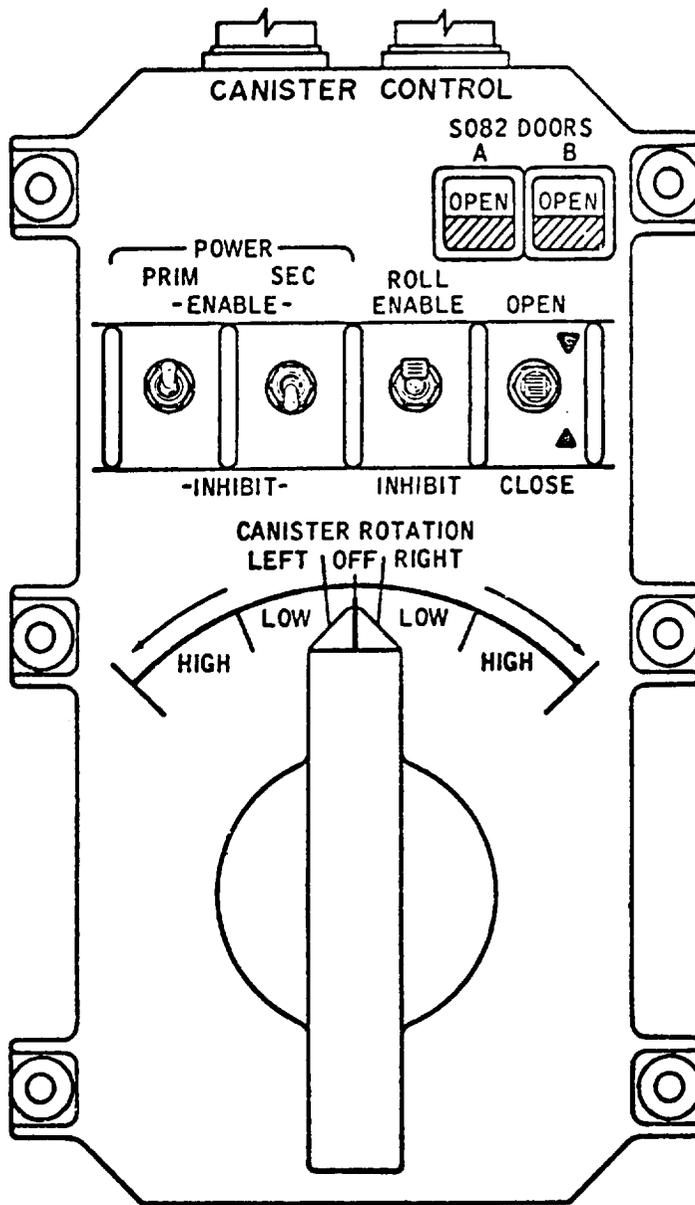


Figure II.H-3 ATM EVA Rotation Control Panel

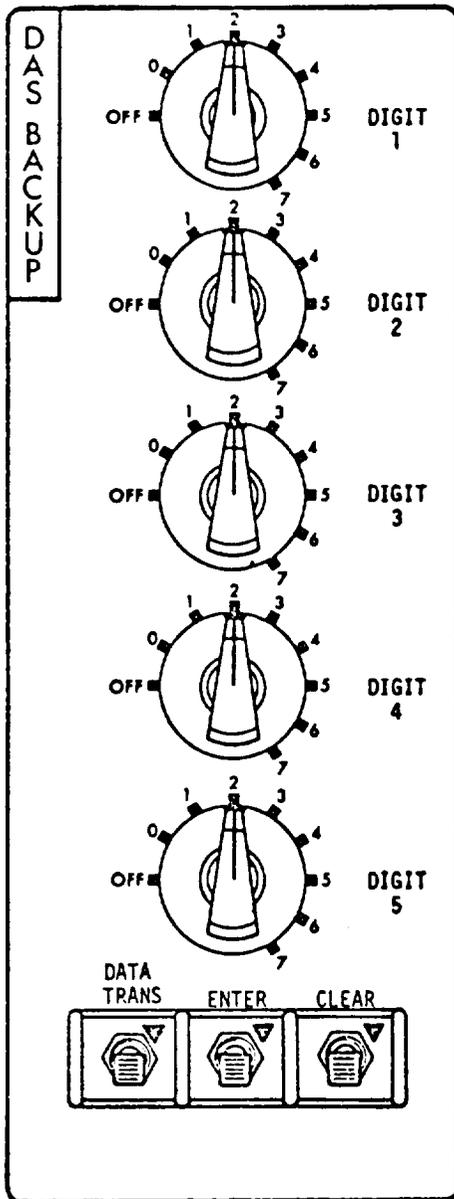


Figure II.H-4
 Backup ATM EVA Rotation
 Control Panel

I. Caution and Warning System

The Saturn Workshop Caution and Warning (C&W) System provided the crew with visual displays and audible tones when specified cluster parameters reached out-of-tolerance conditions.

The original C&W System design concept consisted of a Call and Warning Unit and an alarm tone generator that was part of the Gemini Voice Control Center. Initially, only 12 parameters were to be monitored. System sensors and associated electronics were nonredundant. Later, the system was modified to expand the Emergency and Warning Unit capability to monitor 35 parameters, which included fire and rapid loss of vehicle pressure. Redundant sensors and electronics were added together with two klaxons for providing emergency tones. Finally, the C&W System was expanded to contain redundant subsystems within a caution and warning unit. Seventy-six selected parameters were monitored and four separate audio tones, along with visual indicators, were provided.

The contractor effort regarding the system included the following:

- The design and development of the C&W System.
- Performance of the integration effort required for defining and evaluating the AM, ATM, MDA and OWS C&W System for compliance with cluster requirements.
- Qualification of system components and verification of system performance.
- Performance of C&W System support activities for all Skylab missions.

1. Design Requirements. The finalized requirements for the C&W System are defined in the Cluster Requirement Specification, RS003M00003, Appendix H. A summary of these requirements is presented below.

a. C&W System Purpose. The C&W System for the cluster (CSM docked to SWS) was required to monitor the performance of itself (voltage only) and other selected systems parameters, and alert the crew to imminent hazards or out-of-limit conditions that would jeopardize the crew and compromise primary mission objectives, or, if not responded to in time, could result in loss of a system. Parameters monitored by the C&W System were to be categorized as either EMERGENCY, WARNING, or CAUTION. When any of the parameters reached the predetermined out-of-tolerance level appropriate visual and acoustical signals were to be activated. See Table II.I-1.

b. C&W Subsystems. Each vehicle (SWS or CSM) C&W System was to consist of the following:

(1) Emergency Subsystem. The emergency subsystem was to alert the crew to defined emergency conditions that could result in crew injury or threat to life and required immediate corrective action, including predetermined crew response. The subsystem was to alert the crew by

Table II.I-1. Caution and Warning System Parameters

ITEM/PARAMETERS	MONITORED MODULE	CRITICALITY (SEE NOTE 1)	LIGHT LABELING	C&W TRIP POINTS
AM-ECS				
1. Sieve A Bed 1/2	AM	C	Sieve Temp High	425 deg F \leq T \leq 450 deg F
2. Sieve B Bed 1/2	AM			
3. PPO ₂ 1	AM	W	PPO ₂ Low	145.2 mmHg \leq PPO ₂
4. PPO ₂ 2	AM			\leq 169.6 mmHg
5. Pri Cool Pump 1	AM	W	Pri Cool Flow	N/A
6. Pri Cool Pump 2	AM			
7. Pri Cool Pump 3	AM			
8. Sec Cool Pump 1	AM	W	Sec Cool Flow	N/A
9. Sec Cool Pump 2	AM			
10. Sec Cool Pump 3	AM			
11. Cluster Pressure	AM	W	Cluster Press Low	4.5 psia \leq P \leq 4.7 psia
12. Sieve A PCO ₂	AM	C	Sieve Out PPCO ₂ High	2.87 mmHg \leq PCO ₂ \leq 5.93 mmHg
13. Sieve B PCO ₂	AM			
14. Sieve A Gas Flow	AM	C	Sieve Flow	17.3 cfm \leq F \leq 24.9 cfm
15. Sieve B Gas Flow	AM			
16. Sieve A Timer	AM	C	Sieve Timer	Timer Power Interrupt \leq 45 ms
17. Sieve B Timer	AM			
18. OWS Gas Flow	AM	C	OWS Gas Interchange	35 cfm \leq F \leq 55 cfm
19. Condensate Tank Δ P	AM	C	CNDST Tank Δ P	0.3 psid \leq Δ P \leq 0.8 psid
20. Pri Cool 47 deg Valve	AM	C	Pri Cool Temp Low	35.1 deg F \leq T \leq 40.9 deg F
21. Sec Cool 47 deg Valve	AM	C	Sec Cool Temp Low	35.1 deg F \leq T \leq 40.9 deg F
22. Pri Cool Loop Temp	AM	C	Pri Cool Temp High	114.2 deg F \leq T \leq 125.8 deg F
23. Sec Cool Loop Temp	AM	C	Sec Cool Temp High	114.2 deg F \leq T \leq 125.8 deg F

NOTE 1: E = Emergency; W = Warning; C = Caution

Table II.I-1 (continued)

ITEM/PARAMETER	MONITORED MODULE	CRITICALITY (SEE NOTE 1)	LIGHT LABELING	C&W TRIP POINTS
INTEGRATED EPS				
24. Reg Bus 1 Low	AM	W	Reg Bus 1 Low	24.5 Vdc \leq V $<$ 25.5 Vdc
25. Reg Bus 1 High	AM	W	Reg Bus 1 High	30.38 Vdc $<$ V \leq 31.62 Vdc
26. Reg Bus 2 Low	AM	W	Reg Bus 2 Low	24.5 Vdc \leq V \leq 25.5 Vdc
27. Reg Bus 2 High	AM	W	Reg Bus 2 High	30.38 Vdc \leq V \leq 31.62 Vdc
28. ATM Bus 1 Low	ATM	W	ATM Bus 1 Low	24.5 Vdc \leq V \leq 25.5 Vdc
29. ATM Bus 2 Low	ATM	W	ATM Bus 2 Low	24.5 Vdc \leq V \leq 25.5 Vdc
30. C&W Power 1	AM	C	C&W Power	3.7 Vdc \leq V \leq 4.3 Vdc
31. C&W Power 2	AM	C	C&W Power	23 Vdc \leq V \leq 25 Vdc
32. C&W Sig Cond Power	AM	C	C&W Power	26 Vdc \leq V \leq 22 Vdc $\frac{+2\%}{-2\%}$ -22 Vdc \leq V \leq -26 Vdc $\frac{+2\%}{-2\%}$ 5.2 Vdc \leq V \leq 4.8 Vdc $\frac{+2\%}{-2\%}$
33. Emergency Power 1	AM	C	Emergency Power	23 Vdc \leq V \leq 25 Vdc
34. Emergency Power 2	AM	C	Emergency Power	3.7 Vdc \leq V \leq 4.3 Vdc
35. Emergency Sensor 1	AM	C	Emerg Sensor Power	24.5 Vdc \leq V \leq 25.5 Vdc
36. Emergency Sensor 2	AM	C	Emerg Sensor Power	24.5 Vdc \leq V \leq 25.5 Vdc
37. OWS Bus 1 Low	OWS	C	OWS Bus 1 Low	23.03 Vdc \leq V \leq 23.97 Vdc
38. OWS Bus 2 Low	OWS	C	OWS Bus 2 Low	23.03 Vdc \leq V \leq 23.97 Vdc
39. Battery 1 70% DOD	AM	C	Bat Charge Low	N/A
40. Battery 2 70% DOD	AM	C	Bat Charge Low	N/A
41. Battery 3 70% DOD	AM	C	Bat Charge Low	N/A
42. Battery 4 70% DOD	AM	C	Bat Charge Low	N/A
43. Battery 5 70% DOD	AM	C	Bat Charge Low	N/A
44. Battery 6 70% DOD	AM	C	Bat Charge Low	N/A
45. Battery 7 70% DOD	AM	C	Bat Charge Low	N/A
46. Battery 8 70% DOD	AM	C	Bat Charge Low	N/A

Table II.I-1. (continued)

ITEM PARAMETER	MONITORED MODULE	CRITICALITY (SEE NOTE 1)	LIGHT LABELING	C&W TRIP POINTS
ATM-ACS				
47. ACS-Overrate	ATM	W	Cluster Aft	N/A
48. ACS-Thruster Stuck				
49. ACS-CMG Saturate				
50. ACS-Auto TACS Only Option	ATM	C	ACS Malfunction	N/A
51. ACS-2nd/3rd Rate Gyro Failure				
52. ACS-Computer Self Test Failure	ATM	C	Computer Malf	N/A
53. Computer X-Over				
54. ATM Coolant Fluid Temp	ATM	C	ATM CNST Thermal	44.9 deg $F < T \leq 45.1$ deg F 54.9 deg $F < T \leq 55.1$ deg F 149.6 deg $F < T \leq 150.36$ deg F 24 psid $\leq \Delta P \leq 26$ psid
55. ATM Coolant Htr Temp				
56. ATM Coolant Pump ΔP				
EXTRAVEHICULAR ACTIVITY				
57. EVA LCG-1 Pump ΔP	AM	W	EVA 1	2.5 psid $\leq \Delta P \leq 5.5$ psid 31.986 deg $F < T \leq 35.014$ deg F
58. EVA LCG-1 H ₂ O In Temp				
59. EVA LGC-2 Pump ΔP	AM	W	EVA 2	2.5 psid $\leq \Delta P \leq 5.5$ psid 31.986 deg $F < T \leq 35.014$ deg F
60. EVA LCG-2 H ₂ O In Temp				
MISCELLANEOUS				
61. CSM 1	CSM	W	CSM	N/A
62. CSM 2				
63. Crew Alert 1	AM	W	Crew Alert (R)	N/A
64. Crew Alert 2				

Table II.I-1. (continued)

ITEM/PARAMETER	MONITORED MODULE	CRITICALITY (SEE NOTE 1)	LIGHT LABELING	C&W TRIP POINTS
EMERGENCY				
65. MDA/STS Fire 1	MDA/STS	E	MDA STS Fire (R)	\triangle_4 32-38 counts/sec
66. MDA/STS Fire 2				
67. AM AFT Fire 1	AM	E	AM AFT Fire (R)	\triangle_4 32-38 counts/sec
68. AM AFT Fire 2				
69. OWS Fwd Fire 1	OWS	E	OWS FWD Fire (R)	\triangle_4 32-38 counts/sec
70. OWS Fwd Fire 2				
71. OWS Exp Fire 1	OWS	E	OWS EXP Fire (R)	\triangle_4 32-38 counts/sec
72. OWS Exp Fire 2				
73. OWS Crew Qtrs Fire 1	OWS	E	OWS Crew QTRS Fire (R)	\triangle_4 32-38 counts/sec
74. OWS Crew Qtrs Fire 2				
75. Rapid ΔP 1	AM	E	Rapid ΔP (R)	$0.10 \text{ psi min} \leq \frac{\Delta P}{\Delta T} \leq 0.11 \text{ psi min}$
76. Rapid ΔP 2				

NOTES: 1. E = Emergency,
W = Warning,
C = Caution

2. Brackets denote use of 'or' gates to minimize channel complexity.

3. (R) denotes items repeated in OWS.

\triangle_4 Fire sensor trip point is adjustable from 25 counts/sec to 75 counts/sec.

triggering an acoustical alarm system in the vehicle atmosphere and by providing typical warning category outputs. The emergency subsystem was to be dc-isolated from the caution and warning subsystem.

(2) Caution and Warning Subsystem. The caution and warning subsystem was to alert the crew to defined caution or warning out-of-tolerance conditions. All outputs of the caution and warning subsystem were to be displayed on the caution and warning system panel(s) and were to generate the appropriate caution or warning tone for routing to the crewman earphones and speaker intercom assemblies (SIAs). The caution or warning conditions were defined as follows:

(a) Caution. Any out-of-limit condition or malfunction of a cluster system that could result in not meeting primary mission objectives or could result in loss of a cluster system if not responded to in time. Crew action was required although not immediately.

(b) Warning. Any existing or impending condition or malfunction of a cluster system that would adversely affect crew safety or compromise primary mission objectives. Immediate action by the crew was required.

2. Functional Description. The design features and major components of the C&W System are described in the following paragraphs; detailed description of this system is contained in the Skylab Caution and Warning Technical Manual, MSFC 40M35701.

a. Skylab C&W System. The Skylab C&W System consisted of C&W Systems installed in both the SWS and the CSM. Each system provided the crew with visual displays and audio tones when selected parameters reached out-of-tolerance conditions. In the docked configuration, the two C&W Systems interfaced by means of discrete contact closures to provide for cluster wide monitoring of selected parameters. The C&W System equipment used to monitor these parameters is shown in Figure II.I-1. The SWS C&W System control and display panels are shown in Figure II.I-2.

(1) SWS C&W System. The system monitored the performance of specified vehicle systems and alerted the crew to hazards or out-of-limit conditions. The SWS C&W System used two independent subsystems; a caution and warning subsystem for monitoring various system parameters, and an emergency subsystem for detecting fire or rapid loss of pressure.

(2) CSM C&W System. The CSM contained a separate C&W System for monitoring thirty-six critical system parameters in the CSM. An out-of-tolerance condition in the CSM resulted in the generation of audio tones and the illumination of visual displays in the CM. In addition, the CSM C&W System provided redundant contact closures to the SWS C&W System. Upon receiving the CSM inputs, the SWS C&W System activated the corresponding SWS warning audio tone and illuminated the visual displays to alert the crew so that corrective action could be taken. The audio tones continued until the SWS C&W System was reset; however, the CSM closure remained until reset from within the CM. The CSM C&W equipment

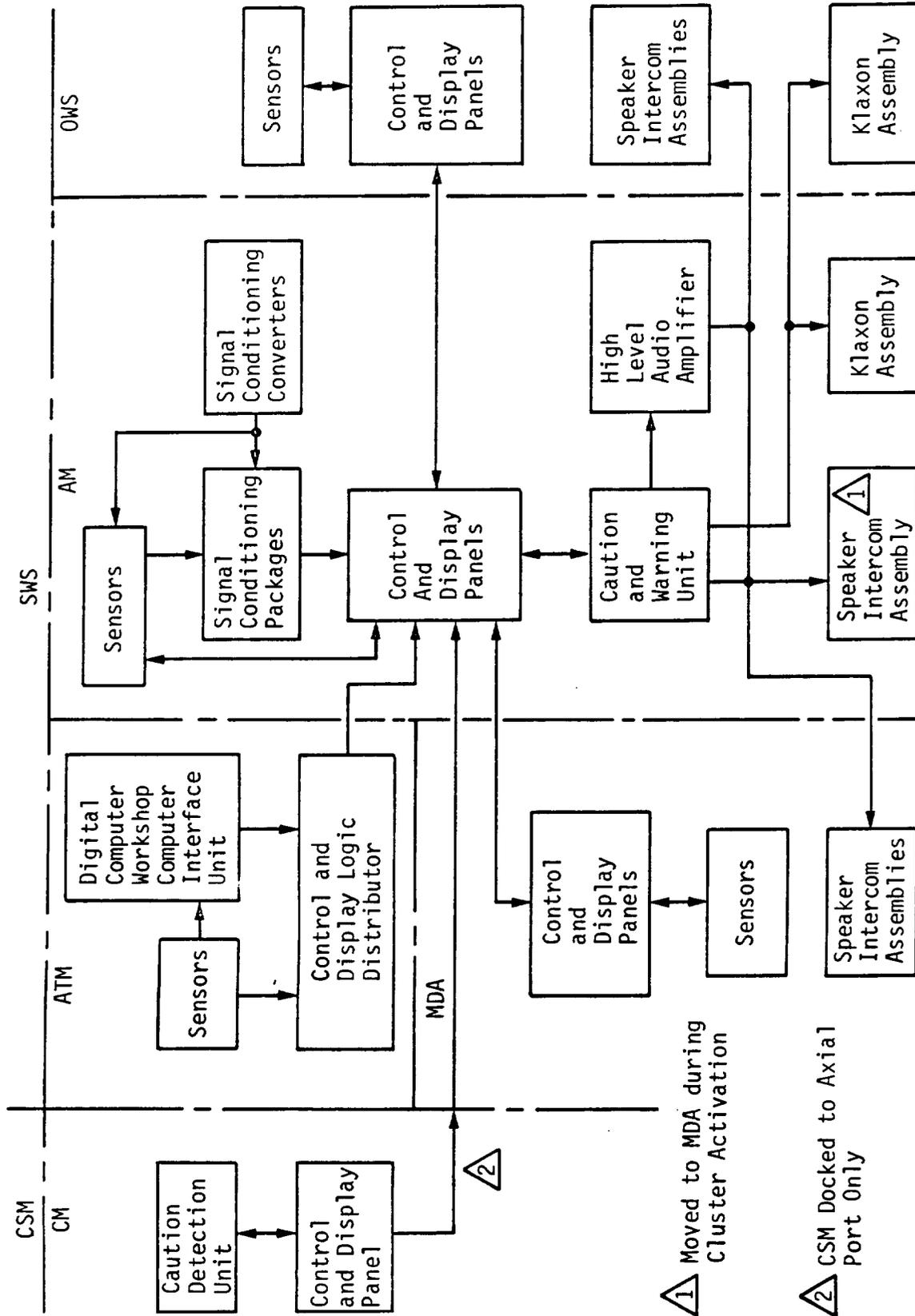


Figure II.I-1 Cluster Caution and Warning System

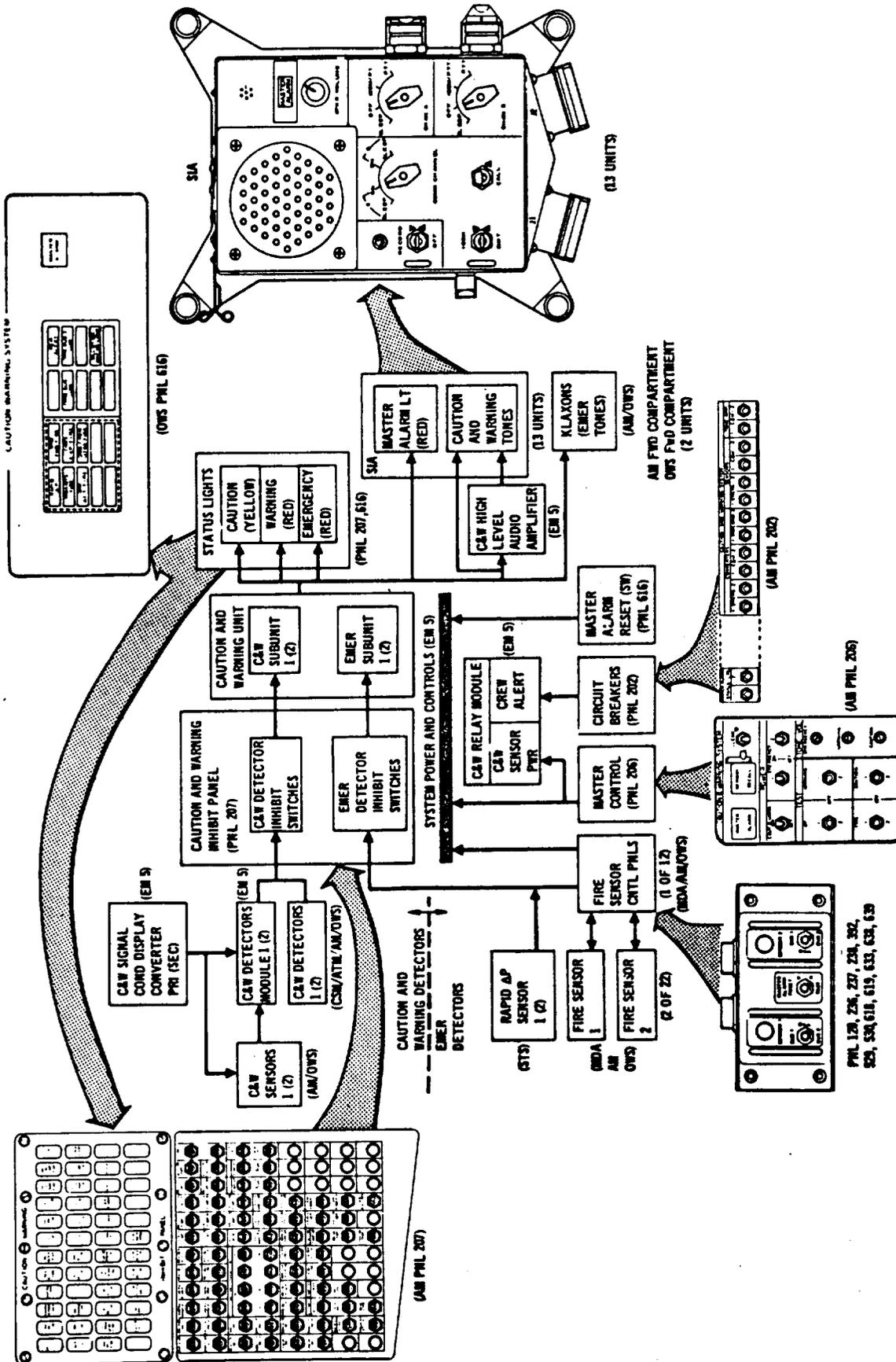


Figure II.I-2. Caution and Warning Controls and Displays

and operation is discussed in detail in the Skylab Operations Handbook, Volume I, SM2A-03-SKYLAB-(1).

b. Major SWS C&W Components. The SWS C&W System was made up of the following major components:

(1) Circuit Breaker Panel 202. Circuit Breaker Panel 202 housed the SWS C&W System related circuit breakers. This panel was located in the STS. Fourteen circuit breakers were used for controlling power to various components of the C&W System. These circuit breakers provided power to the redundant components in the system from two independent energized buses.

(2) Control and Display Panels. A total of fifteen separate control and display (C&D) panels were provided in the SWS for control, display, operation, and testing of the caution and warning and emergency subsystems. Three of these panels were used for control and display of both subsystems, whereas, the remaining twelve were used for control and display of the fire detection portion of the emergency subsystem.

(a) Control and Display Panel 206. The major power and control switches for the SWS C&W System were located on Panel 206 in the STS. The master alarm red telelight switch was illuminated when either a caution, warning, or emergency parameter was activated. When depressed, the master alarm telelight switch provided a reset signal to the C&W unit electronics to terminate the audio tones, extinguish all master alarm telelight switches and master alarm status lights, and remove the telemetry closures. In the emergency subsystems, this reset signal also extinguished the parameter identification lights when the parameters had returned within limits. The memory recall amber telelight switch was used to indicate that caution and/or warning parameter(s) that activated the C&W subsystem had been stored in memory. Depressing the memory recall telelight switch caused the identification light(s) to be illuminated for the parameter(s) that were stored in memory. This provided for the identity of short term C&W subsystem activations after the fact. The clear switch erased the memory circuitry in the C&W unit and extinguished the recall telelight switch. Three power switches were provided for powering the SWS C&W System. One switch was used to control power to the C&W subsystem and the other two switches were used for the emergency subsystem. Four test switches were provided for testing the C&W subsystem electronics, audio tone, and visual displays. Three volume controls were also provided for controlling the intensity of the emergency, warning, and caution tones.

(b) Display and Inhibit Switch Panel 207. The parameter identification lights and inhibit switches were located on Panel 207, also in the STS.

There were forty parameter identification lights used to aid the crew in identifying which parameter or system had gone out-of-tolerance. Emergency and warning parameter lights were colored aviation red while caution parameter lights were colored aviation yellow. Each display had two bulbs for redundancy, with each bulb being driven by separate power sources.

Each parameter monitored by the C&W System had a corresponding inhibit switch(s) on Panel 207. The inhibit switches were used to disable a malfunctioning circuit or input signal without disabling other active parameter inputs. They could also be used to determine the nature of the malfunction in those cases where more than one parameter shared a common identification light. There were 76 double-pole single-throw inhibit switches used on this panel.

(c) OWS Repeater Panel 616. This panel was located in the Experiment Compartment of the OWS. The panel contains one master alarm reset telelight switch (aviation red) that performed the same function as the master alarm telelight switch on AM Panel 206.

Ten parameter identification lights were used to aid the crew in identifying various parameters of systems that had gone out-of-tolerance. Each display contained two bulbs that were powered from separate power sources. The lights were color-coded the same as those appearing on the AM Panel 207.

(d) Fire Detection Control Panels. The fire sensor control panels (Panels 120, 236, 237, 238, 392, 529, 530, 618, 619, 633, 638, and 639) provided the controls for operation and test of the fire sensor assemblies. A typical panel is shown in Figure II.I-2.

Each panel had the capability of controlling two sensors. Two power switches were provided, one for each sensor, which allowed manual selection of one of two normally energized buses capable of supplying power to the respective sensor. A master alarm reset/test switch was provided for testing the sensor(s) and resetting the SWS C&W System. A red display lamp was provided for each of the two sensors that illuminated upon activation of the sensor and remained illuminated until power was momentarily removed from the sensor. The bulbs and lenses on the panels and the panels themselves could be replaced in flight. Two spare panels (complete with lenses and bulbs) and eight lenses and bulb assemblies, were stowed in the OWS for inflight replacement. In cases where one panel controlled only one sensor, a clip was provided for covering the unused control and display. When both sensors were energized, the panel dissipated 5.5 watts of power.

(3) Caution and Warning Unit. The C&W unit contained redundant C&W subunits and redundant emergency subunits. Each subunit was powered from a normally energized bus and was protected by an independent circuit breaker. Each C&W Subunit used 36 caution and 26 warning parameter inputs and provided 22 caution and 17 warning outputs for parameter identification lights. Each emergency subunit had 12 parameter inputs and provided 12 outputs for parameter identification lights. The capacity of the C&W unit, including growth capability, is shown in Table II.I-2.

Each subunit provided a current limited control voltage that was dc-isolated from the input bus. The control voltages from the two C&W subunits were added together by diodes to provide one combined control voltage, but the emergency subunits control voltages remained isolated. These voltages were routed to their respective C&W System parameter closures and

Table II.I-2. Caution and Warning System Parameter Inputs

INPUT TYPE	INPUT CAPACITY**					
	CHAN- NELS	GATES				TOTAL
		SINGLE	"2 OR"	"3 OR"	"8 OR"	
AM Caution	16	8***	5	2	1	32
*OWS Caution	4	4****	0	0	0	4
AM Warning	11	4	2	4	1***	28
*OWS Warning	1	0	1	0	0	2
Optional-AM Caution or Warning	7	2	5***	0	0	12
*Optional-OWS Caution or Warning	1	0	1	0	0	2
*Emergency-Fire	5	0	5	0	0	10
*Emergency-Pressure	1	0	1	0	0	2

NOTES: *These input types cause identification light outputs for the OWS in addition to those on the AM caution and warning system panel.

**The quantities given are for one half on the caution and warning system; the system electronics (excluding sensors) are completely redundant.

***One Spare Channel

****Two Spare Channels.

control switches for operating the C&W System. The control voltage returns for all subunits were isolated from each other and all other vehicle returns.

The C&W unit was coldplate mounted on AM Electronics Module 5. In the standby mode, the unit consumed a maximum of 100 watts of power.

(4) High Level Audio Amplifier. A high level audio amplifier (HLAA) was added to the SWS C&W System to provide caution and warning tones in the event of a failure to the buses powering the speaker intercom assemblies. The HLAA amplified the caution or warning tone from the C&W subunits and applied the tone directly to the speakers in the speaker intercom assemblies. The HLAA contained two amplifiers for redundancy; each amplifier was powered from a normally energized bus and was protected by an independent circuit breaker. The HLAA consumed ten watts of power when in the standby mode and a maximum of 100 watts when amplifying the caution and warning audio signals. The HLAA was coldplate mounted on AM Electronics Module 5.

(5) Signal Conditioning Packages. Two signal conditioning packages (C&W instrumentation packages) were provided for redundancy. The signal conditioning packages conditioned preselected signals from the C&W System sensors and voltage levels from monitored buses. A total of 19 caution and 17 warning parameters were routed to the signal conditioning packages. These signals were routed into level detectors that were preset to trigger when a designated signal level was exceeded. The level detector

turned on a relay driver that provided a relay closure to the C&W system. All level detectors in the signal conditioning packages except the PCO₂ low detectors received their basic power from the C&W signal conditioner converters which supplied +24 Vdc regulated voltages to the detectors. Power for the relays and the PPO₂ low detectors were powered directly by the EPS control buses. The signal conditioning packages were coldplate mounted on AM Electronics Module 5. The total level detector power consumption was 3.7 watts per package. In addition, each energized relay required approximately one watt of power.

(6) Signal Conditioner Converters. The dc-dc converters converted the EPS bus voltage into + 24 Vdc and +5 Vdc regulated voltages. The +24 voltages were used to power the level detectors in the signal conditioning packages and the differential amplifiers in the PPCO₂ sensors. The +5 volts were used to power the EVA suit inlet water temperature sensors and the AM coolant loop temperature sensors. Two signal conditioner converters were used for redundancy and were mounted on AM Electronics Module 5. Each converter consumed 11.5 watts of power.

(7) ATM Digital Computer/Workshop Computer Interface Unit (ATM Provided). The ATM digital computer provided the primary computational capability for the ATM pointing control system and the cluster attitude control system. There were redundant ATM digital computers that interfaced with the workshop computer interface unit (WCIU) in the ATM. The WCIU provided the input/output buffering and automatic switch-over capability for the two digital computers. Each computer contained subroutines for determining out-of-tolerance conditions and for setting the discrete output registers in the WCIU. The discrete output registers determined the status of the relays that provided the discrete C&W closures. Each ATM digital computer weighed 100 pounds and dissipated 165 watts. The WCIU dissipated 105 watts.

(8) Control and Display Logic Distributor (ATM Provided). The control and display logic distributor housed the relays which were used to provide the C&W closures in the ATM. The combined C&W control voltage, routed via redundant paths from the ATM/AM interface to the C&D logic distributor, was applied to two control buses within the distributor. These control buses provided the C&W control voltage for the various C&W closures. The unit accepted discrete inputs for energizing the various relays and provided redundant outputs that were routed across the ATM/AM interface through separate connectors. The control and display logic distributor dissipated 40 watts of power.

(9) Speaker Intercom Assemblies. Thirteen speaker intercom assemblies (SIAs) were located through the SWS for intercommunications between the crew and communications with the ground. These assemblies contained a red master alarm status light on each unit and were also used for reproducing the caution and warning tones. The caution tone was a continuous 1 kHz frequency while the warning tone was 1 kHz frequency, modulated at a 1.4 Hz rate. The C&W tones were routed to both the SIA speaker and

the crewman communication umbilical connectors. In the active mode each SIA consumed 4.0 watts of power. Two flight spares were stored in the OWS for inflight replacement.

(10) Klaxon Assemblies. The klaxon assemblies contained redundant speakers, which converted the emergency signals into audio tones. The emergency audio tones were coded to permit the crew to readily identify the nature of the emergency situation. The fire tone was a siren while the rapid delta P tone was a buzzer. For isolation purposes, one speaker in each klaxon assembly was driven by Emergency Subunit 1; whereas, the second speaker was driven by Subunit 2. One klaxon assembly was located in the forward tunnel of the AM and the other in the forward compartment of the OWS.

(11) Sensors. Two sensors, i.e., fire and rapid delta P, were unique to the SWS C&W System. A description of these sensors follows. The remaining sensors used by the C&W System were previously developed and are described under the Instrumentation System, paragraph II.G.

(a) Fire Sensor Assembly. Detection of fire conditions aboard the SWS was accomplished by 22 fire sensor assemblies (FSAs) located throughout the pressurized compartments. The fire sensor assembly consisted of an ultraviolet (UV) fire sensor and a quick release adapter plate which allowed easy installation and replacement. There were two FSAs located in the MDA, eight FSAs located in the STS, and twelve FSAs located in the OWS. The FSAs located in the MDA and OWS were used to provide general area coverage, whereas, those in the STS were used for viewing particular modules. Each fire sensor assembly was a self-contained unit whose operation was controlled by a fire sensor control panel (FSCP). The FSAs were designed with an optical field-of-view of 120 degrees included cone angle. The sensors, though not totally redundant, were mounted in such a manner as to provide as much coverage overlap as possible. A fire detected by any of the FSAs would result in a generation of an emergency alarm by the C&W System. Six FSAs were stored in the OWS for flight replacement.

1 Fire Sensor Description. The sensors detected the UV emission from flames and provided for initiation of an emergency alarm when the UV intensity exceeded the detector threshold level. Flames emit large amounts of photons in the 1800 to 2800 Å wavelength band, which is the region of sensitivity for a UV fire sensor.

The sensor consisted of two UV radiation sensing tubes and the associated electronics for conditioning the signals. A twin-tube approach was used to preclude false fire alarms with passage of the Skylab through the earth's radiation belts. One sensing tube monitored background particulates incident upon the system while a second tube monitored both the background particulates and ultraviolet radiation. The pulse rate out of each tube was conditioned by the electronics and filtered to obtain a dc voltage proportional to the pulse rate. The difference between the dc voltage representing the UV detector tube and the background tube was a measure of the UV flux emitted from a fire source. An emergency alarm

was initiated when the difference in tube outputs exceeded a preselected value. A statistical analysis of the design, based on estimates of radiation levels expected to be encountered in the Skylab orbit, indicated that a threshold of 35 counts/sec and a time constant of one second would preclude more than one false alarm for each 56 day mission. To compensate for the unexpected, however, the FSAs were designed with a gain adjust having the capability to select a sensitivity setting from 25 to 75 counts/sec, in 10 count increments. Typical FSA response time to UV input equivalent to a 50 microampere standard flame at distance of ten feet was one second.

The emergency alarm activated by the FSA had two forms. One was switch closure to the fire sensor control panel (FSCP), which in turn initiated a relay closure for the C&W control voltage that activated the C&W unit. The other emergency signal generated by the sensor provided an electrical ground for a display light located on the FSCP. Extinguishment of the fire resulted in the relay opening. The electrical ground output for the display light remained latched on after a fire was sensed and could only be reset by temporarily removing power from the sensor.

Preflight system verification tests of the fire sensor operation were accomplished during ground tests via a UV light source and the panel mounted test switches. In flight, partial circuitry tests were performed using the FSCP test switch or the C&W system test fire switch on AM Panel 206.

2 Sensor Selection. Although an abundance and variety of commercial fire sensors existed, it was found that little had been accomplished in developing space qualified devices. Devices subject to an intensive study included a correlation spectrometer (gaseous products), ultraviolet and/or infrared sensors (flame), and temperature sensors (heat). The ultraviolet radiation detector was selected.

The results of the study indicated that detection of ultraviolet radiation emitted during the ignition stage of a fire provided better overall sensitivity, response time and coverage than other type flame detectors. In addition, UV was considered the better parameter for detecting flames, primarily from background considerations, i.e., the UV radiation from the sun was determined to be less likely to trigger false alarms than the infrared radiation given off by any hot body on board the vehicle.

(b) Rapid Delta P Sensor. Detection of rapid decompression of Skylab pressure was performed by redundant rapid pressure loss sensors. Should the cluster pressure decrease at a rate of 0.1 psi/minute or greater, an emergency alarm was generated. This particular pressure decay rate was selected to permit time for emergency action. Typically, a meteorite puncture of the vehicle or a large rupture of the vehicle would be the cause of a rapid leak rate. The detectors were located behind the teleprinter paper storage container in the STS.

1 Sensor Description. The rapid pressure loss sensors consisted of a variable reluctance absolute pressure transducer and

associated electronics. The electronics buffered the absolute pressure transducer signal to the AM telemetry system, differentiated the pressure signal to obtain a rate of pressure change for the telemetry system, and energized a relay to provide contact closures to the emergency control voltages when the pressure decay rate exceeded 0.10 psi/minute. The trip point could be adjusted before installation via a potentiometer located on the side of the sensor. Application of 28 Vdc via the delta P test switch on AM Panel 206 activated a self-test mode in the detector, which simulated electrically an excessive pressure loss and allowed verification of all electronics downstream of the pressure transducer. The sensor consumed 5.6 watts of power.

2 Sensor Selection. The rapid pressure loss sensor design used was selected following an intensive investigation of available sensors. Due to rigid schedule requirements, sensing devices that required limited development effort and methods with similar application were sought. The devices and methods reviewed included:

Detection of high leak rates which exceeded the makeup capability of the cabin pressure regulators using pressure switches.

Detection of pressure changes across a capillary restriction using a low range differential pressure transducer.

Analysis of the sound spectrum associated with escaping gas as a function of orifice size, direction, pressure differential, etc.

Differentiation of the output of an absolute pressure transducer referenced to cabin pressure.

The absolute pressure transducer/differentiator sensing scheme was selected primarily because of its excellent response time and its ability to directly convert rate information from cabin pressure measurements.

c. Telemetry. Individual discrete parameters were provided from each subunit to enable ground control to distinguish when a caution, warning, fire or rapid delta P alarm had been generated. Analog data associated with each CWU converter voltage output was also provided. These parameters, in conjunction with the selected vehicle systems telemetry parameters identified in the Instrumentation System, paragraph II.G, were used to determine system status and to resolve system anomalies.

3. Design Verification. Verification of the Caution and Warning System design requirements was successfully completed during the course of the testing program. The testing phase on the flight hardware employed a comprehensive program of tests. These tests began at the component level, both in-house and at vendor facilities, and continued through module interface, systems, systems interface, and systems integration testing. Completion of the testing program was accomplished at the launch site.

a. Contractor Tests. A large part of the system consisted of various types of sensors supplied by outside vendors who were required to verify conformance to the contractor component Specification Control Drawings (SCD). All sensors were required to pass contractor Preinstallation Acceptance (PIA) Tests for the Instrumentation System.

Manufactured equipment was also tested and included the C&W instrumentation packages and the dc-dc converters. The individual printed circuit card assemblies were tested before installation in the instrumentation packages. Other subassemblies such as the parameter display panel, switch and circuit breaker panels, and associated wire bundles were subjected to manufacturing mechanical and electrical checks and inspections before integrated system level testing.

Contractor PIA tests on the C&W unit and high level audio amplifier were waived; however, contractor personnel at the vendor facility monitored unit testing. The contractor system level test flow utilized to verify the performance of the C&W System is shown in Figure II.I-3.

During systems evaluation testing, C&W System input/output signal handling, sensor trip point levels, and compatibility with other systems (i.e., audio, TM, ECS, EPS, DCS, and coolant) were verified. The C&W interface parameters were checked during the systems assurance test. The test also verified AM/MDA C&W functions end-to-end and supported all AM/MDA systems in an EMC check. AM/MDA C&W interfaces were rechecked after installation of MDA equipment that arrived late. Simulated flight test permitted activation, monitoring, and power down of the C&W System in the manner planned for the mission. Further EMC checks were supported by the C&W System as a part of this test. During the altitude chamber test, the C&W System was checked for proper responses to simulator inputs during an unmanned run, and functionally checked for visual and audio indications at simulated altitude by the flight crew. Before shipment, the EREP was reinstalled, and manned orbital mode and EMC tests were repeated as a part of an abbreviated simulated flight.

b. Problems and Solutions. Testing of the C&W System exposed a nominal number of problems. The following discusses these by subsystem.

(1) Alarm Tone Variations in Frequency and Quality. The C&W alarm tone quality varied, became less clear, and changed in frequency during system validation. Troubleshooting indicated an intermittent condition having the effect of a short on the C&W System High Level Audio Amplifier No. 2 output. The circuit was monitored during subsequent testing. During simulated flight the tone degradation recurred. The C&W System High Level Audio Amplifier, Serial Number (S/N) 100, was removed from the vehicle. A functional test was then performed that verified that the system No. 2 output was defective. Unit S/N 101 was subjected to the same functional bench test, met all requirements and was installed on the vehicle. S/N 100 was found to contain resistors that have incorrect values installed in the No. 2 subsection of the amplifier. All additional units were verified to have the correct parts installed. The discrepant parts in S/N 100 were

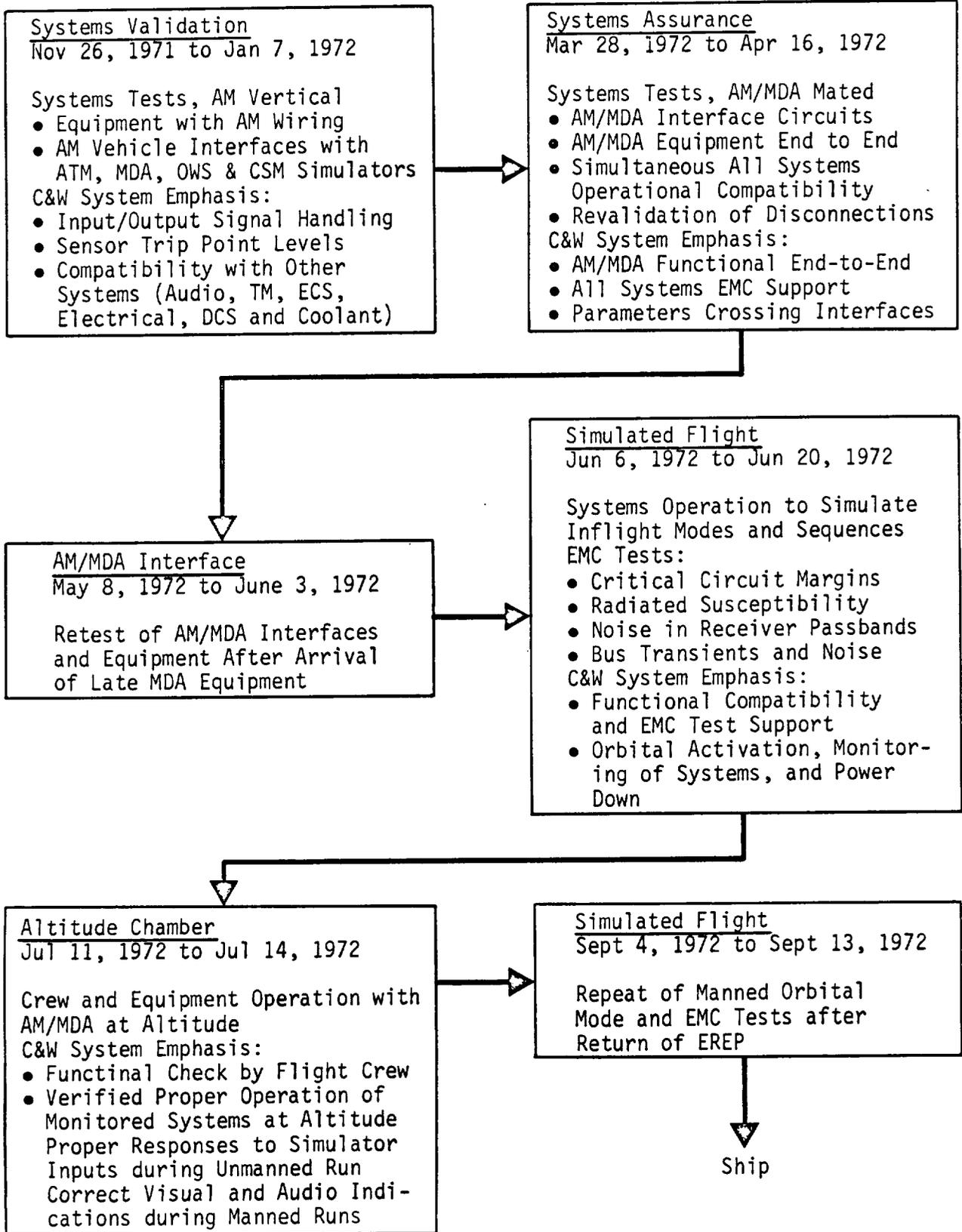


Figure II.I-3 Caution and Warning System Test Flow

causing intermittent operation of the short circuit protection circuitry, which resulted in the changes in tone amplitude and frequency.

(2) Erratic Gas Flowmeter T/M Parameter. During system validation, gas flow sensor parameters F205, F209, F210, and F211 had erratic outputs and indicated below normal flow rates. Investigation of this condition indicated that the flowmeters had improper shielding. In addition, the OWS gas interchange sensor (Parameter F205) was improperly located in the duct. The RF type shielding was changed to audio shielding on all four gas flow sensors and the OWS gas interchange sensor was relocated. The C&W gas flow trip points were also lowered to further reduce the probability of false alarms.

(3) Unexpected Caution and Warning Power Light. The parameter identification light illuminated when the Panel 207 signal conditioner inhibit switch was placed to the enable position during system validation. Laboratory tests found that a short had developed between a component and ground on a printed circuit card assembly. A new circuit card assembly was installed and the system retested.

(4) Primary Coolant Low Temperature Below Specification. During system assurance, C&W System temperature parameter trip points were below specifications on the primary coolant low parameter and on the EVA 1 and EVA 2 inlet temperature low parameters. The C&W instrumentation package trip points were found to be lowered by the presence of 2 to 4 MHz noise observed between vehicle structure and the dc returns from the dc-dc converters to the instrumentation packages. The problem was successfully resolved by the addition of jumper plugs to both C&W signal conditioner (instrumentation) packages. The jumper plugs contained capacitors installed between the pins connected to structure and the dc power returns. These capacitors shorted the conducted noise.

(5) Noise Perturbations on MDA Temperature Parameters. Various MDA temperature parameters experienced up to 15 counts of noise at random intervals on the T/M outputs during altitude chamber tests. Testing revealed the C&W unit internal dc-dc converters were generating the noise due to their electronic switching action. The noise was coupled into the MDA temperature parameter T/M lines in the vehicle wire bundles. Capacitors installed between the C&W telemetry output signal return lines and chassis ground and between the C&W telemetry output signal return lines and chassis ground and between the C&W subunits signal ground and chassis significantly reduced the noise coupled into the MDA temperature parameters. Modifications were performed on all C&W units to incorporate the internal capacitors.

(6) No Secondary Coolant Flow Alarm. A C&W System alarm did not occur when the secondary coolant pump A switch was placed to on during altitude chamber tests. The problem was isolated to a reed switch failure. The pump containing the defective reed switch was removed and replaced.

(7) Two C&W System Alarms not Recallable from Memory.

During descent from altitude, two separate C&W System alarms occurred that could not be recalled from memory to be identified. Retest and troubleshooting at ambient altitude after the run could not repeat the condition. Memory recall circuitry functioned correctly in all cases. During crew debriefing, it was stated that following the first alarm the memory clear switch had been inadvertently actuated before attempting memory recall. The crew believed the memory recall sequence was performed correctly after the second alarm; however, the parameter identification light did not illuminate. Because the problem could not be repeated, it was categorized as an unknown condition. The problem never recurred during subsequent testing.

(8) Rapid Delta Pressure Alarms from RFI. The rapid delta P C&W alarm triggered at various times during simulated flight EMC tests. It was found that the rapid delta P sensors were susceptible to low frequency variations in RF field strength of VHF transmitters. False alarms occurred as a result of the sensor detecting the RF variations induced on the sensor leads. Problem resolution was accomplished by installing new wire bundles, which incorporated RF filtering and shielding, between the sensors and vehicle pressure bulkhead.

(9) Secondary Coolant Temperature Low Alarm. A secondary coolant temperature low alarm occurred during simulated flight. The sensor was found to have a low resistance short to structure. The defective sensor was removed and replaced.

(10) Lack of EVA No. 2 Pump Delta P Alarm. The EVA No. 2 pump delta P C&W alarm did not occur with zero pressure on SUS loop No. 2. The problem was determined to be a defective sensor that was remaining open. The sensor was removed and replaced.

c. Launch Site Testing. Launch site test requirements for the C&W System are defined in Report MDC E0122, Test and Checkout Requirements Specifications and Criteria for use at KSC, and by the Skylab Integrated System Test Checkout Requirements and Specifications, Document No. TM 012-003-2H. Tests per these requirements were successfully accomplished during the system level and integrated testing performed at KSC.

One significant C&W System problem occurred during KSC testing. During the AM/MDA/CSM interface test, an inadvertent rapid delta P alarm could not be correlated with vehicle activity. The new wire bundles, mentioned in the preceding paragraph had been installed. Duplication of the problem was attempted at the contractor facility. Test results confirmed that the alarm occurred due to fluctuations that existed in the rate output section of the delta P sensor. The erroneous rate output was found to be a function of internal interference in the sensor resulting from the effect of two harmonics heterodyning. The transducer oscillator and the dc-dc converter oscillator, both internal to the sensor, were generating the harmonics. The sensors were modified to synchronize the dc-dc converter oscillators. In addition, filter capacitors were added between the +28 Vdc return and signal return to chassis, and a zener diode was installed

between the +28 Vdc input lines to prevent transients on the sensor voltage regulator inputs.

4. Mission Results. The C&W System operated nominally throughout the Skylab mission and performed all required mission functions. The system successfully monitored all 76 parameters and satisfactorily detected out-of-tolerance conditions. The system was operational for a total of 4011 hours. During this time, the system activated approximately 220 times.

a. Out of the 76 parameters monitored, the only false alarms that activated the C&W System were associated with the fire sensor assemblies. These false fire alarms were attributed to the following factors:

(1) High Temperature. Three false alarms occurred on day 146 shortly after C&W System activation. The source of the alarm was FSA 639-1, which was located in the OWS center sleep compartment. These alarms were attributed to the excessively high ambient temperatures (approximately 145°F) in this area. The FSA was qualified to an operating temperature of 100°F. No additional alarms occurred after the SWS returned to normal operating temperatures following the deployment of the thermal parasol.

(2) High Radiation Levels. Four false alarms occurred during passes through the South Atlantic Anomaly. Dosimeter and proton spectrometer data indicated that at the time the alarms occurred peak radiation levels were encountered. On DOY 147 and 152, two alarms were activated by the No. 1 Cooling Module Fire Sensor (392-1). No additional alarms occurred following reduction in the sensor sensitivity setting from 35 counts/sec to 45 counts/sec. On DOY 365 and 016, two Experiment Compartment Fire Sensors (619-1 and 618-1) activated, respectively. The sensitivity of these sensors was not changed and the alarms did not recur.

(3) Sunlight. The following false alarms were caused by Solar UV radiation entering the vehicle as direct sunlight or as reflected light, i.e., the Earth's albedo.

(a) During the first EVA on DOY 158, OWS cooling module FSA 392-2 activated with entry of sunlight through the opened EVA hatch. Because both OWS cooling module fire sensors are located in the compartment evacuated during EVA, the associated EVA procedures were revised to inhibit both OWS cooling module fire sensors.

(b) Two erroneous fire alarms occurred on DOY 216 and were generated by the ward room FSA 633-2. At the time of the alarm, the Skylab was passing through the South Atlantic Anomaly in a near ZLV attitude with the ward room window sunshade removed. In this configuration, the unprotected window was exposed to earth-reflected UV radiation. Although the SAA radiation level also encountered at the time of the alarms was less than that observed at the time of the SL-2 alarms, i.e., approximately 0.1 vs 0.19 rad/hr, the combination of both conditions was considered sufficient to have caused the alarm. No additional alarms occurred and no corrective action was considered necessary.

(c) Two additional fire alarms occurred on DOY 247. The alarms were caused by ultraviolet radiation coming through the unfiltered OWS SAL window during the UV photography experiment S073/T025.

b. During the Skylab mission, two C&W System related component failures occurred. They were as follows:

(1) FSCP. During the SL-2 mission, one component failure was identified. Side 2 of Fire Sensor Control Panel 392, S/N 10, failed to respond to self-test and was successfully replaced with an inflight spare. The removed FSCP was retained onboard as an inflight spare for reinstallation in panel locations 530 or 619 in the OWS which used only side 1.

(2) Pump Delta P. During SUS Loop No. 1 activation on DOY 218, no C&W alarm was generated from the pump delta P sensing circuitry. This condition confirmed the loss of the EVA LCG-1 pump delta P sensing circuitry suspected to have failed during the SL-2 mission.

c. During the Skylab missions, the C&W System in the AM/MDA U-2 vehicle and the C&W simulation in the Skylab Test Unit (STU) were maintained in a mission support mode at the contractor facility. The Airlock U-2 C&W System configuration was identical to Airlock U-1. Special tests and operational modes were performed as required to support the resolution of problems or suspected problems on the SWS inflight. Data was plotted on all C&W System related parameters to monitor system performance and to observe parameter trends for out-of-tolerance or any erratic operation. These data primarily came from the STU/STDN facility at the contractor. The AM/MDA U-2 and STU were used to support significant mission problems occurring during the SL-2 mission in regard to fire sensor false alarms and OWS Bus 1 and 2 low alarm.

(1) Three false alarms occurred on DOY 146 shortly after activation of the C&W System. Fire sensor assembly 639-1 located in the OWS center sleep compartment was the source of the alarms. Testing was performed at the contractor STU facility on an FSA which failed at a temperature above the qualification temperature of 311°K (100°F).

(2) An OWS Bus 1 and Bus 2 low alarm occurred when the associated CBs opened. The U-2 vehicle was used to perform a test to verify that both Bus 1 and Bus 2 low sense circuits functioned properly. The test was to determine the possibility of a short circuit existing between the circuits due to a wiring incompatibility. Test performance proved the C&W sense circuits performed properly and were not tied together.

5. Conclusions and Recommendations. The following conclusions and recommendations are the results of a review of the C&W System design, the adequacy of the test program associated with this system, and the performance of the C&W System during the Skylab mission.

a. Conclusions. The design and verification of the Skylab C&W System were proved to be effectual in that all required mission functions

were performed satisfactorily. The system was operational during all manned phases of the mission and successfully monitored all 76 preselected parameters, which relieved the crew to perform other assigned activities. The crew reported that the C&W system performed in an outstanding manner and that they were well pleased with all C&W System/crew interfaces; i.e., system control/inhibit switches, audio alarms, indicator lights, parameter categories, memory recall, and system reset capabilities. Of the 76 parameters monitored, only the gas flow, PPCO₂, and CMG Sat parameters activated the C&W System an excessive number of times. The ATM CMG Sat parameter activated frequently during periods of high crew activity and/or ATM rate gyro failures while the PPCO₂ and gas flow alarms resulted from marginal sensing techniques used. Refinement in techniques to accurately measure PPCO₂ and gas flow are required to make these parameters more meaningful.

The number of false alarms generated by the system were minimal and readily explainable. With the exception of the fire alarm activated by the South Atlantic Anomaly that required the reduction in the sensitivity of one FSA (392-2), all other false alarms were due to improper management of the vehicle systems.

b. Recommendations. The following items were identified during system testing and/or mission support activities and are recommended to further improve the capabilities of the C&W System:

(1) Provide the capability to monitor the inhibit switch positions associated with the various C&W parameters via a TM data word. Continual questioning of the crew was required to determine status of the inhibit switches.

(2) Add TM parameter, with ground test capability, to alert ground support personnel that a C&W alarm occurred and was reset while the vehicle was out of contact.

(3) Improve techniques for monitoring PPCO₂ and gas flow to permit meaningful surveillance of these parameters.

(4) Use high level (0-5 Vdc) input signals in lieu of low level (0-20 mv) signals for better noise rejection characteristics.

(5) Stabilize the C&W voltage parameters by balancing the TM output circuitry.

(6) Impose stricter EMI requirements on component design to avoid late design changes as was experienced with the rapid delta P sensor.

(7) Simplify wiring by incorporating circuitry presently contained in the High Level Audio Amplifier into the C&W unit package.

(8) Provide ground test capability for verifying sensors that are unavailable to monitor such as the MOL sieve temperature sensors.

(9) On future applications, add filter networks internal to the rapid delta P sensor and C&W signal conditioner packages.

J. Attitude and Pointing Control System

The prime objective of the ATM Pointing and Control System (PCS) was to accurately point an experiment package towards the sun to obtain scientific phenomena data. The PCS was developed to meet the ATM scientific objectives which required high pointing accuracy and stability under both internal and external disturbance torques. These scientific objectives minimized the use of mass expulsion from the vehicle to reduce the possibility of contamination of the scientific instruments.

The basic PCS (later called the Attitude and Pointing Control System) that was developed provided attitude and pointing control for the clustered vehicle and pointing and control for the gimbale solar experiment package. For the former system, a momentum exchange system consisting of three noncontaminating CMGs provided vehicle control.

The three-CMG cluster and its ancillary equipment were designated the "CMG Control Subsystem". The control system developed for the spar-mounted solar experiments included a gimbal arrangement for control in two axes and an open loop roll control via a ring gear for the third axis. The CMG Control Subsystem provided the dynamic roll control for the latter axis. The spar control system was designated the Experiment Pointing and Control (EPC) Subsystem.

Design implementation of both the CMG Control Subsystem and the EPC Subsystem were subjected to major revisions as mission objectives were altered from their initial conception. It is the objective of the following discussion to trace the PCS history.

1. Workshop Attitude Control System. Prior to the advent of the DWS, the Workshop Attitude Control System (WACS) was to provide control of the cluster immediately after orbital insertion for acquisition of rendezvous and docking attitudes, and for attitude control during un-manned storage periods.

The WACS was to be activated following S-IVB stage passivation, and was to be commanded to assume control of the SWS. Astronaut commands or ground commands would select the WACS control modes, and the necessary control phases.

The WACS would have the capability of sequencing control functions to maneuver the OA for attitude acquisition and to maintain the attitude within specified limits. When commanded, the WACS could inhibit thruster firings while monitoring attitude and rates. Attitude and rate maneuvers could also be commanded by the astronauts.

Following each manned mission, the WACS would be commanded to assume control of the SWS during the storage period. Prior to each manned mission, the WACS would be commanded to orient the SWS for

rendezvous and docking with the CSM. For example, after the AAP-3 CSM had docked, the WACS would be ground-commanded to return the OA to an X-axis perpendicular-to-the-orbit plane (X-POP) attitude and hold until the workshop was reactivated (about 5 days). The WACS would then maneuver the OA to an X-POP Z-LV (Z-axis Local Vertical) attitude in preparation for rendezvous and docking of the AAP-4 LM/ATM. During docking, the CSM Reaction Control System (RCS) would aid the WACS by providing additional rate damping. After docking of the LM/ATM, and deployment of the ATM solar wings, the ATM PCS was to be activated.

After PCS activation, the WACS would be placed in a minimum power consumption condition which would enable the WACS to be reenergized as required. The CSM RCS would be turned on to maneuver the OA to the ATM acquisition attitude. Control of the OA would then be assumed by the PCS.

a. WACS Performance and Design Requirements. Table II.J-1 lists the system performance requirements, with respect to the reference coordinate frame, for each WACS operational mode. It also lists the WACS design requirements, astronaut command authority, and ground command authority.

b. WACS Operation. The WACS, as shown in Figure II.J-1, consisted of the following basic hardware:

- Rate Gyros
- Discrete Horizon Sensors, Conical Horizon Sensors and processing electronics
- Sun Sensors
- Control Computer
- Control Switching Assemblies
- Thrusters
- Control and Display (C&D) Panel

Redundant components and circuitry were provided to meet crew safety and mission success criteria. Table II.J-2 lists the pertinent characteristics and type of redundancy associated with each component.

c. Operational Modes. With the aforementioned equipment, the WACS provided the following operational modes:

- Gravity Gradient
- Storage
- X-POP/Z-LV
- X-POP
- Inertial Hold and Maneuver

The WACS used these modes to maintain the defined reference attitudes in addition to maneuvering through the transitional phases. Additional system functions included the MDA north or south condition of the X-POP and X-POP/Z-LV mode, the inhibiting of thrusters, and biasing during any mode. An astronaut or ground command was required to switch the WACS from one operational mode to another.

Table II.J-1 WACS Requirements

MODE	AXIS	* REQUIRED PERFORMANCE		DESIGN PARAMETERS			ASTER AND GROUND COM AUTHORITY	
		Altitude Accuracy Degrees	Body Rate Degrees/Second	ATT Dead Band Degrees	Rate Crossover Degrees/Second	Rate Ledge Degrees/Second	Rate Degrees/Second	Altitude Degrees
IG	Acquisition	NR	NR	+0.5 +0.5 +0.5	+0.05 +0.05 +0.05	+0.1 +0.1 +0.1	+0.3 +0.3 +0.3	NR
	Maintenance	NR	NR	+0.5 +0.5 +0.5	+0.05 +0.05 +0.05	+0.1 +0.1 +0.1	+0.3 +0.3 +0.3	+20 +20 +20
X-POP/Z-LV	Acquisition	NR	+0.3 +0.3 +0.3	+0.5 +0.5 +0.5	+0.05 +0.05 +0.05	+0.1 +0.1 +0.1	+0.3 +0.3 +0.3	NR
	Maintenance	+2 +2 +2	+0.1 +0.1 +0.1	+0.5 +0.5 +0.5	+0.05 +0.05 +0.05	+0.1 +0.1 +0.1	+0.3 +0.3 +0.3	TBD TBD TBD
X-POP	Acquisition	TBD TBD TBD	NR	+0.5 +0.5 +0.5	+0.05 +0.05 +0.05	+0.1 +0.1 +0.1	+0.3 +0.3 +0.3	NR
	Coarse Maintenance	+5 +5 +5	+0.1 +0.1 +0.1	TBD TBD TBD	TBD TBD TBD	TBD TBD TBD	+0.3 +0.3 +0.3	+20 +20 +20
INERTIAL HOLD AND MANEUVER	Coarse Pointing	TBD TBD TBD	+0.1 +0.1 +0.1	+0.5 +0.5 +0.5	+0.05 +0.05 +0.05	+0.1 +0.1 +0.1	+0.3 +0.3 +0.3	+20 +20 +20
	Fine Pointing	TBD TBD TBD	+0.1 +0.1 +0.1	+0.1 +0.1 +0.1	+0.01 +0.01 +0.01	+0.02 +0.02 +0.02	+0.3 +0.3 +0.3	+20 +20 +20
STORAGE	PMS Operation	NONE +25 +20	NR	NR	NR	NR	NR	NR
	Reacquire	NR	NR	+0.5 +0.5 +0.5	+0.05 +0.05 +0.05	+0.1 +0.1 +0.1	+0.3 +0.3 +0.3	TBD TBD TBD

* With respect to the reference coordinate frame
 ** Minimum allowable tolerance.
 NA - Not applicable
 NR - No requirement
 TBD - To be determined

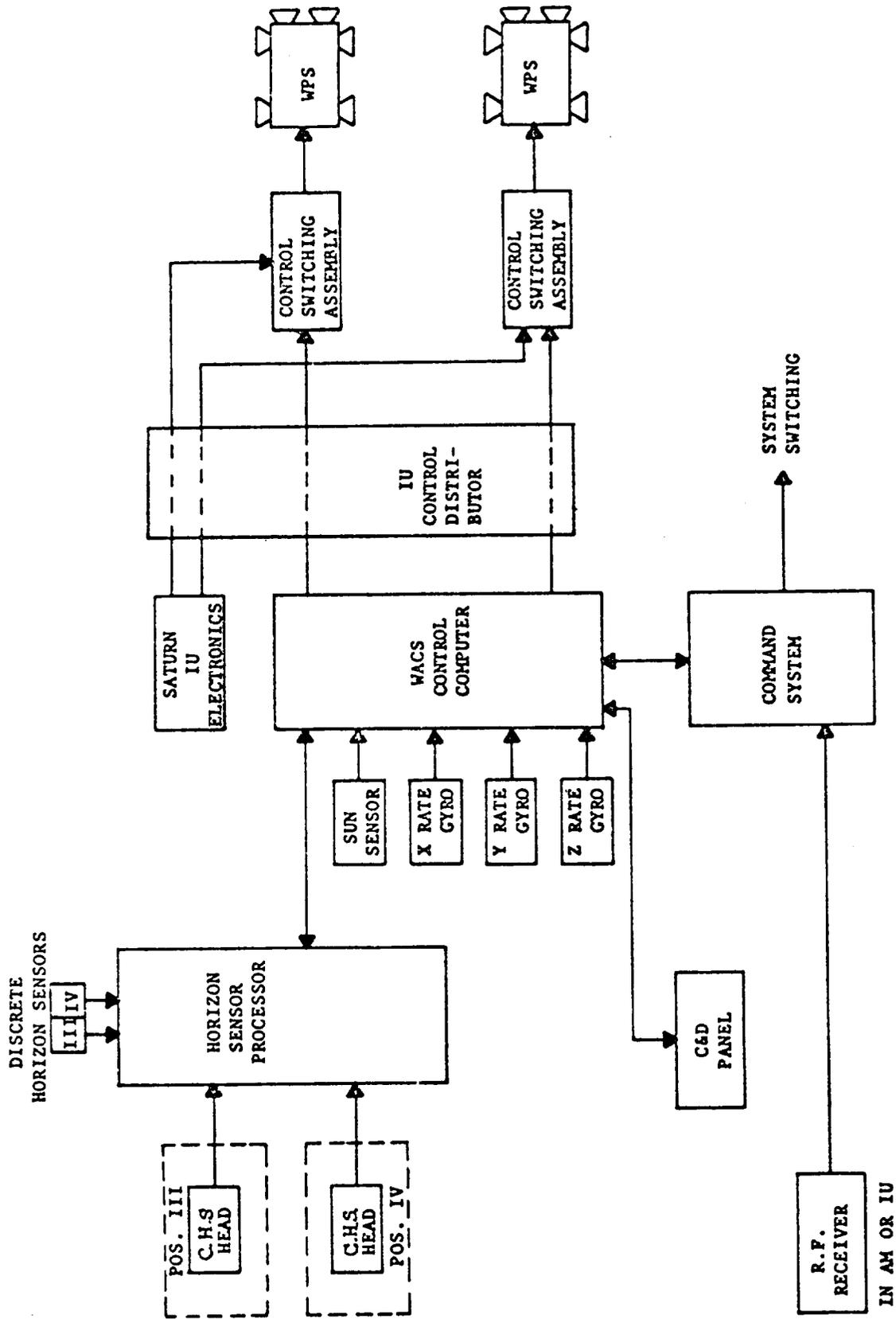


Figure II.J-1 WACS Functional Block Diagram

Table II.J-2 WACS Hardware Complement Summary

COMPONENT	QUANTITY	REDUNDANCY	MAJOR FUNCTION	PRIMARY PERFORMANCE PARAMETER	LOCATION	VOLUME (CU IN PER ASSEMBLY)	WEIGHT (LBS PER ASSEMBLY)	EXCITATION	POWER (WATTS PER ASSEMBLY)
Rate Gyroscope	9 (Note 1)	Pair & Spare	Rate sensor	Rate Sensing Coarse Mod: ± 1 deg/sec Fine Mod: ± 0.045 deg/sec	AM	360	13	28 VDC ± 6	15
Conical Horizon Sensor	4 (Note 2)	Prime-Backup	Attitude Sensor		AM Pos III & IV				
Discrete Horizon Sensor	6 (Note 1)	TMR	Attitude Sensor	0 or 5 VDC	AM Pos III & IV				
Horizon Sensor Processor	1 (Note 3)	TMR	Process Horizon Sensor Outputs		AM				
WACS Sun Sensor	1 (Note 3)	TMR	X-Axis Attitude Sensor		AM Pos I				
WACS Control Computer	1 (Note 3)	Pair & Spare & TMR	Control Loop Signal Conditioning & Mode Switching		AM				
Control Switching Assembly	2 (Note 3)	TMR (Electronics)	Thruster Firing Logic & Malfunction Detection		6-11V AFT SKIRT				
WACS Propulsion System	1 (Note 4)	Prime-Backup	Provide Maneuvering Thrust	22.5 LBS Thrust/Jet	5-11V AFT SKIRT				

NOTE 1 Includes Primary, Secondary and Reference unit in each axis.

NOTE 2 Includes Primary and Secondary unit in each of the two positions.

NOTE 3 Each unit contains required redundancy.

NOTE 4 Contains 12 engines.

2. PCS Engineering Background. The ATM mission, which was to be an extended orbital mission, required that the ATM vehicle roll axis (Z-axis) be collinear with the solar vector. The requirement for extremely precise attitude control during long duration missions eliminated consideration of conventional reaction jet control systems for attitude control. (Practical limitations on minimum impulse vehicle rates obtainable with reaction jet control systems are inconsistent with precision control in the arc-second range. Also, fuel consumption with associated weight penalty precludes the reaction jet control system for long term missions). The CMG, which is a momentum exchange device, was therefore chosen as the controlling device for the ATM vehicle since it offered the advantage of precision attitude control and momentum exchange properties.

The design and development of the PCS was based on evolving ground rules and directives dating from June 1966. Prior to that time proposals were studied (primarily the Ball Brothers Apollo Telescope Optical Mount proposal) in some detail by a small number of MSFC personnel. Visits to Langley Research Center and a study of various CMG systems were conducted during the summer of 1966. A set of ground rules for the project was drawn up in response to directives from the OMSF and included in a PDR in July 1966. This set of ground rules provided for a design using the Langley CMG LM/Rack freefly mode, maximum astronaut usage, maximum Saturn Apollo hardware, a 28-day maximum life, no redundancy, and a 1968 launch. Based on these ground rules, design of a PCS was begun and procurement action for long lead time components initiated. The PCS design (1966) consisted of fine and coarse sun sensors, single analog control computer with switching and logic, three CMGs, CMG electronics and inverters, three rate gyros, hand controller, and analog displays. This system depended on a RCS manual dumping of the CMG bias momentum, visual pointing of the experiments, and voice recording of pointing position. All telemetry was conditioned external to the PCS. Ground commands were decoded in the control computer.

The first major impact occurred when the primary ATM vehicle was clustered. This required increasing CMG momentum, addition to the system of orbital plane reference, and frequent momentum dumping. About the same time, experiment demands and crew motion combined to require a decoupled experiment package mounting with separate controls. It was realized that man-motion disturbances would tax the capability of the CMG subsystem to maintain the experiments' pointing stability requirements. Extensive simulation studies of crew motion disturbance effects were performed. In addition, a roll positioning capability for the experiment package was added. These impacts, along with increased readout needs, added to the analog control computer (a star tracker reference was also added) complexity until a separate electronics box, the Information Correlator Assembly (ICA), was proposed. Study of the ICA design revealed that the minimum complexity was close to that of a small digital computer. After extensive investigation of available computers, procurement approval for a new computer was requested.

Reliability considerations for the long mission times caused a new look to be taken at redundancy. All mission-critical single-point failures were made redundant by switchover capability, and duplex components were added. For example, system redundancy was provided to the point that any component failure that could cause the mission to be aborted, was provided with a backup unit, or an alternate subsystem configuration could be selected by the astronaut to allow PCS operation without performance degradation; e.g., two CMGs, in lieu of three, could control the ATM vehicle. Some backup units operated in parallel with the primary units, while others were not activated unless the primary unit(s) failed. Selection of the backup was controlled by the astronaut actuating appropriate switches on the C&D Panel.

Other increases in complexity were required as results of simulation analysis indicated new problem areas. The resultant PCS was entirely different in capability, ease of operation, reliability, and complexity; however, the same basic accuracy and performance were maintained or improved.

3. Description of Initial PCS. The initial design of the PCS, was developed to meet the high accuracy pointing and stability requirements established by the desired experiment requirements. These latter requirements were to be maintained by the PCS under the influence of external and internal disturbance torques such as gravity gradient, aerodynamic drag, and vent disturbance and crew motion, respectively.

The primary ATM vehicle configuration consisted of an CSM, SWS, AM, MDA, and an LM/ATM joined together in a "cluster" configuration. An alternate, or backup configuration consisted of the CSM and LM/ATM docked together. Alternate vehicle configurations under investigation included a free-flying LM/ATM and a tethered configuration. For the latter concept, the LM/ATM was connected to the S-IVB/MDA/CSM combination with either a rigid or a soft tether. The S-IVB/MDA/CSM was passively stabilized, primarily using the gravity gradient field, and the LM/ATM was actively controlled to point toward the sun using the CMG control system. The free-flying LM/ATM and the tethered design study configurations were eventually discarded. For the cluster or backup vehicle configuration the PCS provided three-axis attitude stabilization and maneuvering capability of the ATM vehicle in either configuration and provided the capability of pointing the experiment package at desired locations on the surface of the solar disk, or its outer perimeter, for the purposes of solar experimentation. The subsystem was to be activated in orbit after the vehicles comprising the ATM vehicle configuration were assembled and docked. It assumed control after the CSM had oriented the vehicle with the Z-axis aligned to within 9 degrees of the center of the sun with the X-axis approximately in the orbit plane. The PCS maintained vehicle control for the duration of the solar experimentation period and for the subsequent storage period.

The ATM PCS consisted of the CMG control system, the EPS, and the Roll Positioning Mechanism. The PCS design that evolved was influenced

by many factors, the prime requirement of being able to meet the high accuracy pointing specifications for the various vehicle configurations and the concomitant internal and external disturbance torques. The significant external disturbance torques are those due to gravity gradient and aerodynamic drag, of which the former disturbance was more pronounced (an order of magnitude); the internal disturbance torques were those created by crew motion. Because of the earth orbital environmental influences, the cluster attitude had to be held to a fixed position relative to the orbital plane. To significantly reduce the gravity gradient bias torques, the vehicles principal axis of minimum moment-of-inertia had to be constrained to lie close to the orbital plane while the ATM experiment package pointed towards the sun. Since this constrained the vehicle attitude about the line of sight to the sun (Z-axis), the roll repositioning requirement was obtained by an RPM that could be driven ± 95 degrees relative to the ATM rack and then locked to any position within said range. To meet the pitch and yaw pointing requirements, a two-axis gimballed EPS with a maximum range of ± 3 degrees was required. The EPS provided primarily experiment package isolation from the relatively large vehicle perturbations from nominal crew motion disturbances.

The CMG control system provided ATM vehicle maneuvering capability (manual or automatic) and attitude stabilization about three axes. This system was chosen primarily because of performance benefits with respect to both dynamic response and compensation of cyclic disturbance torques caused by gravity gradient and aerodynamic effects. Most passive control schemes would not have the required accuracy and could not develop sufficient torque to meet the dynamic performance requirements. During experimentation periods, use of CMGs prevents optics contamination that would result from a reaction control thruster exhaust.

a. PCS Design Requirements (1966). For the PCS design requirements, roll was defined as the angular rotation about the line of sight from the experiment package to the center of the sun, and pitch and yaw were the small angular deviations of the experiment package with respect to this line of sight. The design requirements were as follows:

(1) Command pointing requirements:

- Roll command position (θ_r): ± 10 arc min.
- Pitch and yaw command position ($\theta_{p,y}$): ± 2.5 arc sec

(2) Control system pointing and stability requirements about the commanded reference point:

- Pitch and yaw attitude: ± 2.5 arc sec for 15 min of operation.
- Pitch and yaw rate (maximum jitter rate): ± 1 arc sec/s
- Roll excursion: ± 7.5 arc min for 15 min of operation
- Roll rate (maximum jitter rate): ± 1 arc min/s
- Maximum acquisition time: 10 min

- Offset pointing:

Pitch and yaw repositioning capability from any point to any other point within a ± 20 arc min square nominally centered on the solar disk.

Roll repositioning capability of ± 90 degrees from the North Ecliptic Pole solar reference position.

Time not to exceed one minute, including settling time at the new attitude, for an offset maneuver in either pitch and yaw or roll.

- Time resolution: manual trim to within ± 2 arc sec. Where applicable, these values were considered to lie within the 1σ probability bounds and were to be achieved in the presence of nominal expected astronaut motion during intervals of experiment data gathering only.

b. Initial PCS Operation. The PCS made use of various sensor and sensor output processing in determining the vehicle attitude errors. These sensors and their locations are noted in Table II.J-3. The interface of these sensors (and output processing) with the remainder of the PCS is shown in Figure II.J-2. This figure also depicts the operational modes of the control system as described below.

Table II.J-3. Original PCS Sensor Complement

<u>SENSOR</u>	<u>LOCATION</u>	<u>OUTPUT</u>
Acquisition Sun Sensor	Rack	Cluster pitch and yaw attitude.
Fine Sun Sensor	Experiment package	Experiment package pitch and attitude with respect to solar disc.
Canopus Tracker	Rack	Cluster roll attitude with respect to the suns line of sight.
Integrators on Output of Rate Gyros	Rack	Cluster pitch and yaw attitude.
Rate Gyro	Rack	Cluster roll rate.
Rate Gyros	(2) Experiment package	Experiment package pitch and yaw rates when EPS is active. Cluster pitch and yaw rates when EPS is caged.

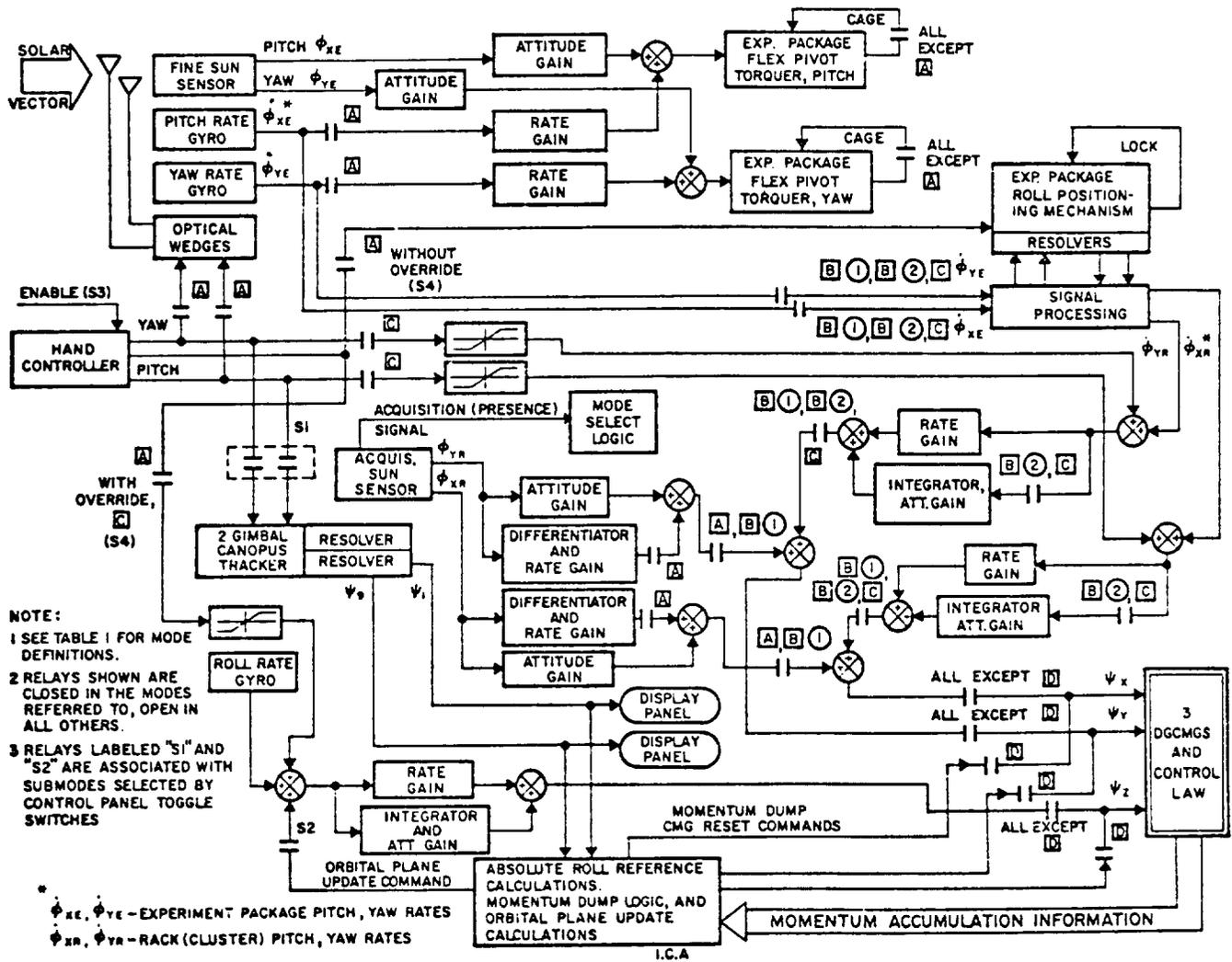


Figure II.J-2 ATM Control System Mode Definition Block Diagram

Two gyros are located on the experiment package to detect pitch and yaw rates. An additional rate gyro is located on the rack to detect roll rate. During the daylight portion of the orbit, cluster pitch and yaw attitude angles (vehicle X and Y axes, respectively) are sensed by an Acquisition Sun Sensor (Acq. SS). During the night portion, these angles are obtained by integrating (in the ATM control computer) body-fixed rate gyro output signals which first undergo a coordinate transformation. By differentiating the Acq. SS outputs during the day and utilizing the body-fixed rate gyros at night, pitch and yaw rate damping for the CMG control system was obtained. Roll attitude angle (Z-axis rotation) for the cluster was generated by integrating the rack-mounted roll rate gyro.

The EPS consisted of a pitch/yaw "flex-pivot" gimbal controlled by two redundant torque motors per axis. Error signals derived from the FSS and the experiment pitch and yaw rate gyros drove the actuators. The Roll Positioning Mechanism (RPM) provided roll attitude positioning of the experiment package through a roll offset drive motor attached to the supporting ring of the experiment package. The astronaut could rotate the experiment package through ± 95 degrees. The roll freedom was required to align optical slits of certain experiments with the suns limb while maintaining the desired orientation of the principal axis of minimum inertia with respect to the orbital plane.

Figure II.J-2 also shows the rack-mounted Canopus star tracker which was used to meet the ± 10 arc min accuracy requirement of the experiment package roll reference computation with respect to Ecliptic North. In addition, the tracker compensated for long term roll reference gyro drift and could provide the attitude reference for calculating the required roll command to keep the clusters principal axis of minimum inertia close to the orbital plane. The tracker was mechanically gimballed in two axes through ± 20 degrees (inner pivot) and ± 80 degrees (outer pivot). Since Canopus is off the Ecliptic South Pole by 14.5 degrees, an inner gimbal freedom of ± 20 degrees was selected to permit Canopus acquisition and lock at any time during the year when the line of sight was not occulted by the earth. The outer gimbal freedom of ± 80 degrees was dictated by the constraint of maintaining the vehicles principal axis of minimum inertia approximately in the orbital plane, by the orbital plane parameters, by the celestial geometry, and by cluster orbital assembly alignment tolerances. The tracker had $\pm 1/2$ degrees field-of-view in the acquisition mode and could either acquire the star automatically or be driven in a manual search mode by the astronaut. Once star acquisition had occurred, the field-of-view was reduced to ± 10 arc minutes.

The ATM Control Computer (ATMCC) was a multipurpose analog assembly. It was an integral part of the CMG, EPS, and RPM systems. The general functions of the ATMCC were to accept and process error signals from the rack and experiment package-mounted sensors to provide rate plus displacement command signals to the PCS actuators (CMGs and EPS/RPM torquers), and provide configuration switching for various PCS

operational modes. The component also contained the bending mode filters, conditioning electronics for the manual pointing controls and telemetry processing of the required ATMCC parameters, and the necessary electronics for implementing the CMG H-vector control law, the CMG steering law, and caging the CMGs.

c. PCS Operational Modes. Table II.J-4 indicates where the CMG and EPS control systems obtained their attitude and rate information during the various operational modes. Control modes for PCS operation are briefly described as follows:

(1) Experiment Pointing. This mode was to be used during periods of data gathering. The CMG control system would maintain the cluster attitude with the vehicle Z-axis pointed toward the sun. The EPS would be controlled by the FSS error signals. The pitch and yaw optical wedges inside the FSS could be rate commanded via the astronaut control stick for offset pointing of the EPS. In this mode the roll channel of the control stick normally commanded the RPM. The astronaut could override this condition so that the roll channel of command stick commanded the roll axis of the CMG control system. This was desirable in the event a roll attitude of the experiment package was required beyond the ± 95 degree RPM offset range. The astronaut could then maneuver the vehicle slightly to obtain the desired attitude.

(2) Monitor and Acquisition. It was anticipated that periods would exist during daylight operation for which solar experimentation would not be required. The system was then placed in this mode. Both the EPS and RPM were caged, and the CMG control system would maintain the vehicle in inertial hold. This mode could exist during day and night portions of the orbit.

(3) Inertial Hold and Maneuver. In this mode, the astronaut had the capability of maneuvering the entire vehicle, using the CMGs (the EPS and RPM were caged). The CMG control system maintained an inertial hold unless the astronaut commanded an attitude maneuver. For a given attitude command, the CMG control system would maintain that attitude.

(4) Momentum Dump Mode. The EPS and RPM were also caged in this mode. The CMG control system operation was identical to that of the Monitor and Acquisition night mode. Although three-axis attitude error signals were available from the integrators, they were not sent to the CMGs. This caused any attitude perturbations existing after a momentum desaturation period to be removed when the CMG loop was again closed.

d. Initial PCS Design Changes. The next step in the evolving PCS design was to add additional gyros to the ATM rack. The PCS implementation was as shown in Figure II.J-3. The implementation was such that vehicle rate information would no longer be derived, when required, by differentiating the Acq. SS outputs in the ATMCC. The additional

Table II.J-4 Preliminary ATM Mode Definition

MODES	VERNIER SYSTEM			FINE SYSTEM*		
	Pitch and Yaw Attitude	Roll Attitude	Pitch and Yaw Rate	Pitch and Yaw Attitude	Roll Attitude	Pitch and Yaw Rate
Experiment Pointing Mode ¹	Fine sun sensors on experiment package, error signal from optical wedges set by control stick	Roll positioning mechanism set by control stick unless override switch is on; the roll positioning mechanism is locked	Rate gyros	Acquisition sun sensor	Integrate rate gyro unless override is on, then integrate control stick and rate gyro.	Lead network on output of acquisition sun sensor
Monitor and Acquisition Mode	<u>Day</u> ² EPS gimbals caged at zero; wedges zeroed	Locked at last position	Rate gyros active, resolved to rack coordinates	Acquisition sun sensor	Integrate rate gyro	Resolved experiment package rate gyros.
	<u>Night</u> ³ EPS gimbals caged at zero; wedges zeroed	Locked at last position	Rate gyros active, resolved to rack coordinates	Resolved integrated experiment package rate gyros	Integrate rate gyro	Resolved experiment package rate gyros
Inertial Hold and Maneuver Mode	EPS gimbals caged at zero; wedges zeroed	Locked at last position	Rate gyros active, resolved to rack coordinates	Resolved integrated experiment package rate gyros only or rate gyros and control stick	Integrate rate gyro only or rate gyro and control stick	Resolved experiment package rate gyros
Momentum Dump Mode ⁴	EPS gimbals caged at zero; wedges zeroed	Locked at last position	Rate gyros active, resolved to rack coordinates	Resolved integrated experiment package rate gyros	Integrate rate gyro	Resolved experiment package rate gyros

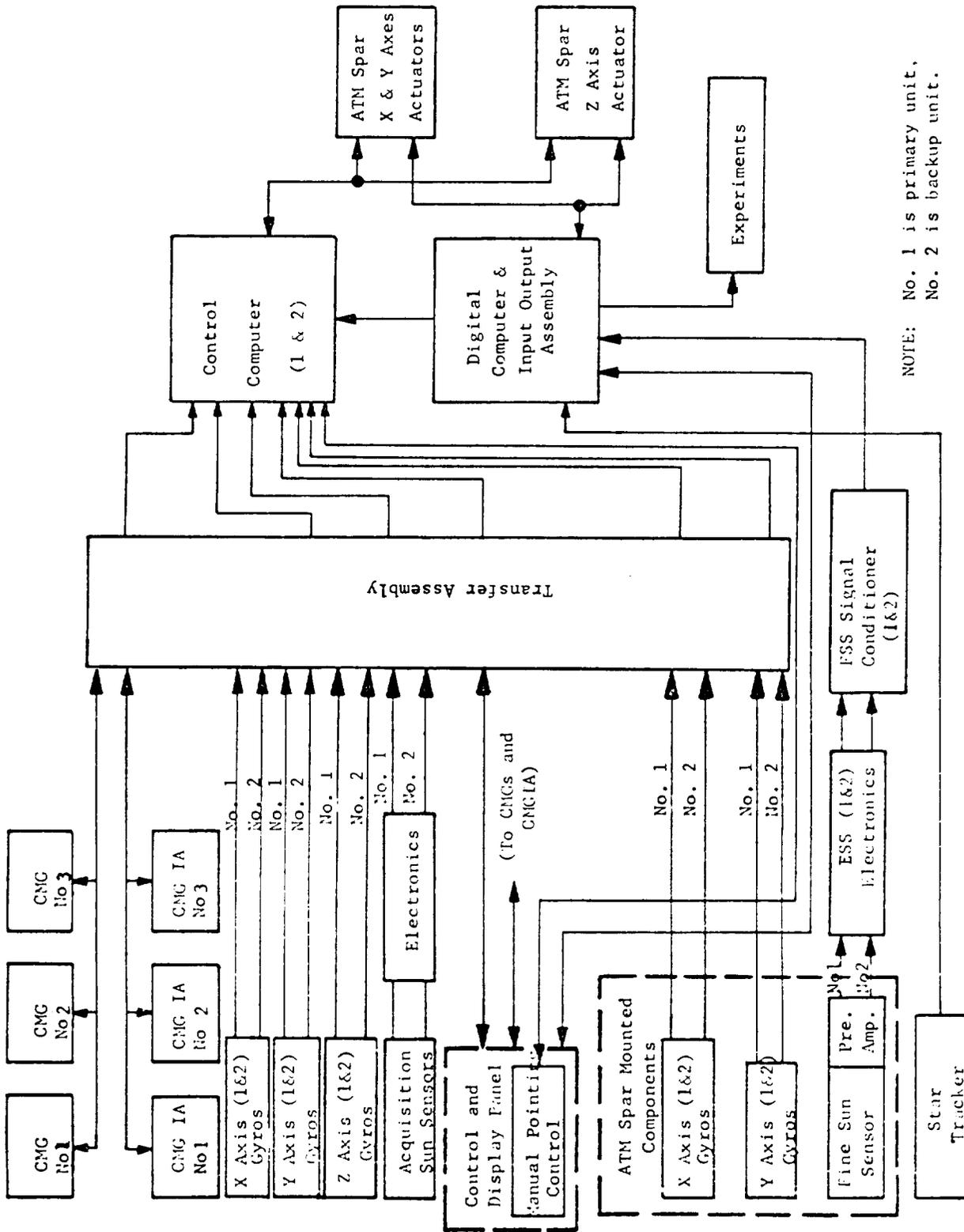
*Roll rate is obtained from the rate gyro.

¹ Automatically switch to night monitor and acquisition mode at clock time.

² Automatically switch to night side hold at clock time.

³ Automatically switch to day at clock time.

⁴ Attitude error signals to CMG control system open.



NOTE: No. 1 is primary unit,
No. 2 is backup unit.

Figure II.J-3 ATM Pointing Control Subsystem

components also obviated the need for the coordinate transformation resolver located on the spar Z-axis. Sensor implementation was such that each primary unit also had a backup. Averaging the sensors outputs for the respective channels did not occur until later. PCS operational mode requirements did not change, nor did their names. The EPS flex pivots were redesigned to allow ± 2 degrees of rotation about the EPC X and Y axes. Rotation about the Z-axis (RPM) was extended from ± 95 degrees to ± 95 degrees, -120 degrees by moving the roll ring gear stop. A further design change moved the stops to the final flight configuration of ± 120 degrees of rotation.

e. Preliminary PCS Performance Requirements. Initially, performance requirements were not completely defined. The requirements tabulated below were preliminary and subject to change.

(1) Control Moment Gyro Control Subsystem

- Z-axis

Pointing: ± 10 arc-min.

Stability: ± 7.5 arc-min for 15 minutes.

Jitter: ± 3 arc-min/second.

Maximum Commanded Vehicle Rate

Cluster Configuration: ± 0.03 deg/sec

CSM/LM/ATM Configuration: ± 0.3 deg/sec

Position input commands through the DAS in increments of 1 degree up to ± 15 degrees.

- X and Y axes

Pointing: ± 4 arc-min.

Stability: ± 6 arc-min for 15 minutes.

Maximum Commanded Vehicle Rate

Cluster Configuration: ± 0.03 deg/sec

CSM/LM/ATM Configuration: ± 0.3 deg/sec

Position input commands through the DAS in increments of 1 degree up to ± 15 degrees.

(2) Experiment Pointing and Control Subsystem

- Experiment Pointing System (EPS)

Gimbal range: ± 2 degrees.

Accuracy: Less than ± 2.5 arc-sec.

Jitter rate: ± 1 arc-sec/second.

Maximum experiment rate: 135.3 arc-sec/second.

Rate loop gain: 90 sec⁻¹

Attitude (Sun Sensor) loop gain: 5.75 to 11.5 sec⁻²

Bandwidth: Not less than 4 Hz

Offset Pointing Capability: ± 20 arc-min/axis.

(3) Roll Positioning Mechanism

- Gimbal range: ± 95 degrees, -120 degrees.

- Rate loop gain: 270 sec⁻¹
- Caging loop gain: 0.50 sec⁻¹
- Rate command capabilities: ± 7 deg/sec
 ± 0.7 deg/sec
 ± 3.5 deg/sec
 ± 0.35 deg/sec

f. PCS Additions Prior to DWS. The requirements for a small general purpose digital computer were being formulated. It was required to perform the following functions for the CMG Control Subsystem, total momentum calculations, CMG momentum management, roll reference computations, telemetry processing, discrete command signal processing, and system timing. Associated with the Digital Computer was an Input/Output Assembly (IOA) which functioned as an interface between the computer and the remainder of the PCS. By that time the EPS and the RPM were descriptively combined and called the EPCS. The CMG Control Subsystem and EPCS, combined, were called the PCS. The Acq. SS was still used during orbit daytime only. It provided vehicle attitude and rate (derived in the ATMCC) information for the X and Y control axes. At orbit nighttime, the EPCS rate gyros were used to provide this information (attitude information was derived in the ATMCC). Switching from Acq. SS to EPC rate gyro(s) reference and vice versa was performed automatically at orbit sunset and sunrise by the Digital Computer. A sun presence signal from the Acq. SS was used by the Digital Computer in determining orbit sunset and sunrise. The Z-axis rate gyro was used on a continuous basis to provide vehicle rate and attitude (derived) information for the Z control axis. The star tracker was to track Conopus or Achernar for determining the vehicle Z-axis reference. The ATM Control Computer conditioned the sensor(s) signals to provide rate plus displacement command signals to the CMGs. The astronaut had the capability of manually controlling the CMG Control Subsystem by means of an address/command keyboard (attitude commands) or a hand controller (rate commands) located on the PCS C&D panel.

There were two backup means for removing CMG accumulated momentum. The primary means was for the astronaut located in the LM to manually input gravity gradient maneuver commands to the CMG Control Subsystem via the address (command keyboard). The alternate backup approach was to use a RCS, located on the CSM or the SWS, for removing the bias momentum. This was to be accomplished via voice link instructions from the LM astronaut to the astronaut controlling the RCS. Based on the instructions, the astronaut would use the RCS attitude control thrusters to introduce desaturation impulses about all three vehicle axes.

The EPS used the FSS to sense the ATM spar attitude errors and the rate gyros for sensing rates. These sensors were hardmounted to the spar which was, and is, the structure which supported the ATM solar experiment package. The ATMCC conditioned the sensors signals to provide rate plus displacement command signals to the flex pivots actuators. Each sensor in the FSS could be effectively biased by the astronaut to offset point the experiment package. The RPM was driven open

loop by the astronaut using rate switches on the C&D panel to control the spar Z-axis. The astronaut repositioned the Z-axis in accordance with experiment demand requirements.

The name and a brief description of each of the control modes for PCS operation were redefined as follows:

(1) Standby Mode. Used during activation and deactivation of the PCS. It placed the Control Computer (CC) into a null state of operation. It was also entered automatically in the event of a system temporary power failure.

(2) Monitor and Acquisition Mode. During orbital daytime, this mode was to be used for maintaining the ATM vehicle minimum moment of inertia axis (X-axis) in the orbital plane and maintain the Z-axis parallel to the sunline. At orbit nighttime, it was to be used to perform gravity gradient momentum dump maneuvers.

(3) Experiment Pointing Mode. This mode was to be used only during solar experimentation (daylight hours). The CMG Control Subsystem stabilized the ATM vehicle with the Rack coarse pointed at the sun, and the EPCS maintained control of the experiment package.

(4) Inertial Hold and Maneuver Mode. In this mode, the ATM vehicle could be maneuvered to any inertial-oriented attitude and held. The CMG Control Subsystem was to be used to orient the vehicle. The EPCS was deactivated, with the experiment package caged and locked.

(5) RCS Momentum Dump Mode. This mode was to be used when gravity gradient maneuvers, manually or automatically, could not be performed to dump CMG bias momentum. A RCS, manually controlled, was to be used to dump the momentum.

4. Wet to Dry Workshop Transition Period. During this period, the PCS was first renamed the ACS, but later called the APCS. Essentially five major areas of the total control system design were impacted in going from the WWS to the DWS configuration, namely:

- Elimination of the LM
- WACS to TACS
- Addition of Z-axis pointing local vertical requirement
- Nested system concept
- Digital control law computations replaced the analog ones

The new mission requirements for the DWS eliminated the LM. The contaminating hot gas WACS Propulsion System (WPS) and the WACS were replaced by the cold gas TACS. The WPS used nitrogen tetroxide as the oxidizer and monomethylhydrazine (MMH) as the fuel, pressurized by nitrogen; the TACS used gaseous nitrogen as the propellant in a blow-down system. The TACS was to provide an earth pointing capability with the Z-axis pointing local vertical and the X-principal axis in the

orbital plane. This attitude was required during pointing of earth resources experiments and during rendezvous and docking of the CSM. The CMG Control System functions were to maintain SI attitude control of the vehicle, maintain dynamic roll control of the experiment spar, provide limited vehicle maneuver capability (e.g., gravity gradient desaturation maneuvers); and provide possible aid in Z-LV maneuvers and hold. The EPC System had to provide the capability to offset point the experiment spar ± 24 arc minutes and provide experiment roll capability of ± 120 degrees relative to the vehicle Y-axis for experiment slit orientation. The CMG and EPC control systems performance requirements, basically, had not changed.

The nested control system configuration consisted of the TACS and the CMG Control Subsystem, and utilized the latter system for control whenever possible. The TACS fired whenever CMG momentum buildup reached 90 percent of its capacity or whenever the TACS rate and attitude deadbands were exceeded. CMG control law solution was to be performed in a digital fashion as opposed to an analog solution in the obsolete ATM Control Computer.

5. APCS Configuration

a. Design Requirements. The final pointing and stability requirements for the CMG and EPC control systems are described below. The two basic changes in the design requirements were in the pointing uncertainty and stability of the X and Y vehicle axes, and in a jitter requirement for the EPCS. The preliminary requirements for said axes included a pointing uncertainty of ± 4 arc minutes versus the present ± 6 arc minutes, and a stability of ± 6 arc minutes as opposed to the present ± 9 arc minutes, each for a 15 minute period. The initial jitter rate for the vehicle control axes was ill-defined causing undue requirements on the control system. Subsequently, this requirement was postponed until a more feasible definition of the jitter rate could be established, as described below.

The TACS was designed to control the attitude of the vehicle during certain events. It was also designed to augment the CMG Control Subsystem when required. A more detailed description of the design requirements for the three systems comprising the APCS may be found in ED-2002-984 Volume III Rev G, APCS Functional Requirements.

(1) CMG Subsystem SI Pointing Requirements

- Z-axis
Pointing Uncertainty: ± 10 arc-min.
Stability: ± 7.5 arc-min for 15 minutes.
- X and Y axes
Pointing Uncertainty: ± 6 arc-min.
Stability: ± 9 arc-min for 15 minutes.

- Momentum Requirements: Under normal operation, the three CMGs shall be capable of storing 6,900 foot-pound-seconds of angular momentum before becoming saturated.

(2) EPCS SI Pointing Requirements

- X and Y axes

Pointing Uncertainty: Less than ± 2.5 arc-sec.

Stability: ± 2.5 arc-sec for 15 minutes.

Gimbal Range: ± 2 degrees.

Experiment Package Rate

Maximum: Greater than 80 arc-sec/second.

Minimum: Less than 2 arc-sec/second.

Rate Loop Gain: 14.6 sec^{-1}

Attitude (FSS) Loop Gain: 141.7 sec^{-2}

Offset Pointing Requirement: ± 24 arc-min/axis
from the center of the solar disk.

- Z-axis (Roll Positioning Mechanism

Pointing Uncertainty: ± 10 arc-min.

Stability: Under control of CMGS/TACS.

Gimbal Range: ± 120 degrees.

Rate Loop Gain: 36.7 sec^{-1}

Rate Command Requirements: ± 7 deg/sec

± 0.7 deg/sec

± 3.5 deg/sec

± 0.35 deg/sec

- Jitter: The EPCS was to be designed so that the jitter at the FSS mounting interface would not exceed ± 1 sec of arc (2 sigma) per any 1 sec of time about the cluster X or Y axis, nor would it exceed ± 3 min of arc (2 sigma) per any 1 sec of time about the cluster Z-axis. Jitter is defined as the spar movement at the FSS mounting interface over a period of any 1 sec of time: i.e., the equivalent angular displacements of the mounting interface occurring within 1 sec of time.

b. APCS Functional Description. The SWS APCS comprises three control subsystems:

- CMG Control Subsystem
- EPC Subsystem
- TACS

Attitude control was accomplished primarily by a combination of the CMG Control Subsystem and the TACS in a so-called "nested" configuration. This nested concept used the CMG Control Subsystem for vehicle control whenever possible. The TACS actuated whenever CMG momentum

buildup approached its capacity (90 to 95 percent of capacity) or whenever the TACS rate and attitude deadbands were exceeded. Early in 1972, the nomenclature "nested" was dropped, but the concept of the TACS augmenting the CMG Control Subsystem was retained through flight. The CMG Control Subsystem, in general, maintained vehicle control while the EPC Subsystem was used during solar experimentation periods. A functional block diagram of the APCS is shown in Figure II.J-4. Two major hardware changes were implemented since the original APCS design of 1969-1970; angular momentum per CMG was increased from 2,000 ft-lb-sec to 2,300 ft-lb-sec in mid-1970 by an additional oscillator in the CMG Inverter Assembly (CMGIA) and in mid-1972 a Memory Loading Unit (MLU) was added. The MLU interfaced with both ATMDCs and was capable of reloading the entire flight program, loading an 8K memory after failure of a memory module, and providing flexibility for real time program change. There were only minor changes to the design and implementation of the remaining hardware.

The six mutually exclusive control modes which are addressable by the C&D Console switches for APCS operation were not changed since the early concepts of the DWS. The name and a brief description of each follow:

- Standby Mode. Used when vehicle control was not required of the APCS, e.g., during CSM control of the SWS. While in this mode the CMG gimbal rates and the TACS firing commands were not activated.
- SI Mode. During orbit daytime, this mode was used for maintaining the vehicles minimum moment of inertia axis (X-principal axis) near the orbital plane and the Z-axis parallel to the sunline. At orbit nighttime, it was used to perform gravity gradient momentum dump maneuvers for desaturating the CMGs.
- Experiment Pointing Mode. This mode was identical to the day portion of the SI mode except that the EPC system could be activated each orbital sunrise and deactivated each orbital sunset.
- CMG/TACS Attitude Hold Mode. In this mode, the vehicle could be maneuvered to any inertial-oriented attitude and held. The CMG/TACS control subsystems were used to control the vehicle. The EPC subsystem was deactivated, with the experiment package caged and locked.
- TACS Attitude Hold Mode. This mode was used to maneuver the vehicle to any inertial-oriented attitude and held using the TACS only.
- Z-LV Mode. This mode was entered during the rendezvous phase of the mission or when earth pointing for experimentation

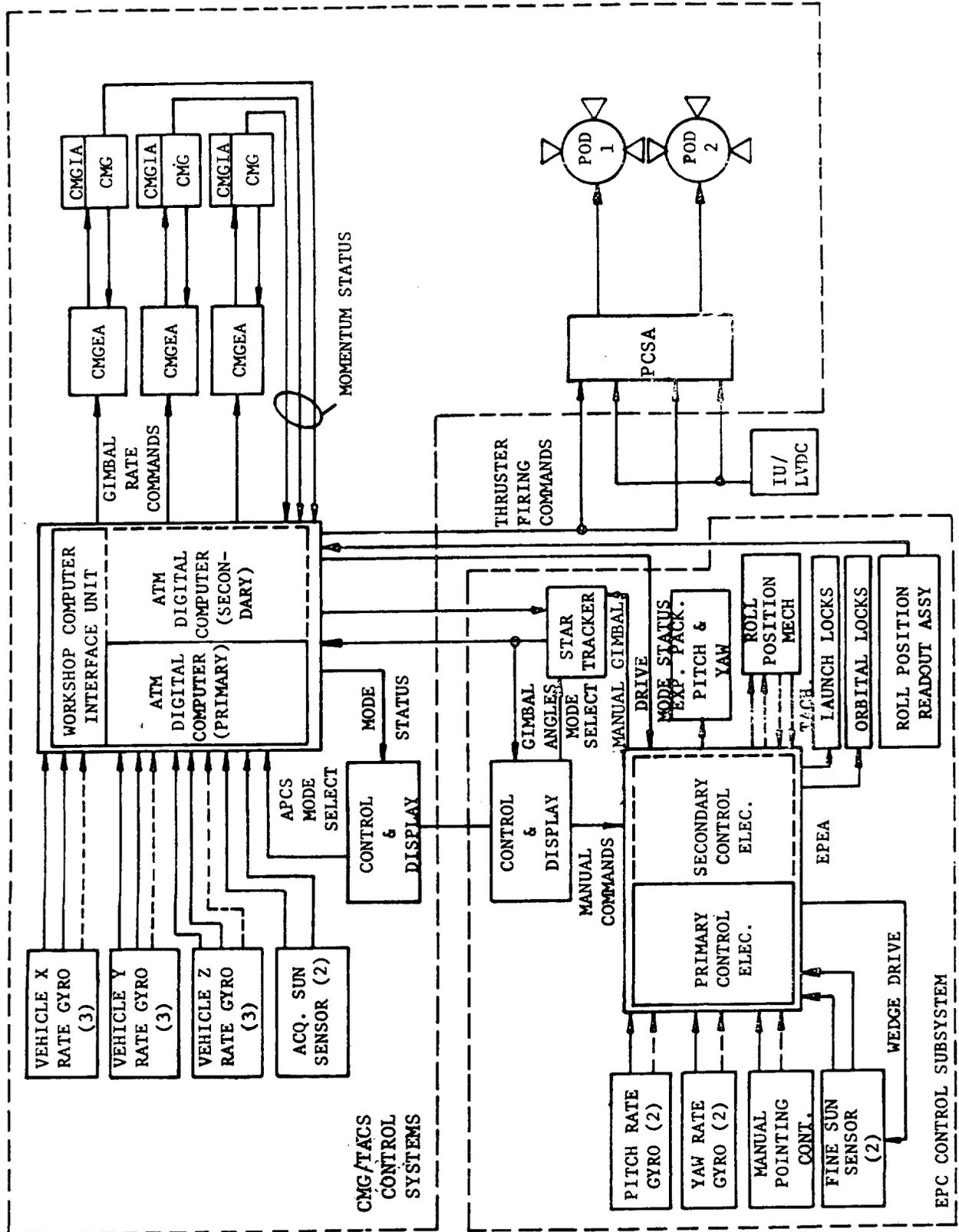


Figure II.J-4 Attitude and Pointing Control System Functional Block Diagram

periods is required. Normal vehicle control was under CMG/TACS configuration.

(1) CMG Control Subsystem. A block diagram of the subsystem is shown in Figure II.J-5. During orbit nighttime, attitude information was always derived from a strapdown computation in the ATM Digital Computer and rack-mounted rate gyros provide rate information. The Acq. SS was used during orbit daytime only. In the time period (late 1969 to early 1970), this sensor provided vehicle attitude information for the X and Y control axes. Subsequently, this sensor updated the strapdown computation for said axes so that the flight configuration always had vehicle attitude information derived from the above mentioned strapdown computation. The ATMDC processed the sensor(s) signals with a CMG control law to generate CMG gimbal rate commands. The astronaut had the capability to manually control the CMG Control Subsystem by means of the DAS on the ATM C&D Console.

Three double gimballed CMGs orthogonally hardmounted to the ATM Rack, were the subsystem actuators. They provided the torques required for vehicle control. Momentum management computations were performed by the Digital Computer. Unloading the bias momentum stored in the CMGs was accomplished by gravity gradient maneuvers, performed automatically during orbit nighttime. The computer monitored the momentum stored by the CMGs about each vehicle axis. After orbit sunset the computer sent rate commands to the CMGs which provided the control torques for achieving the commanded maneuvers. Several such maneuvers were commanded during the occultation period.

(2) TACS. Figure II.J-6 is a simplified functional block diagram of the TACS. If TACS and CMG control were enabled, TACS was used for CMG control monitoring or when the vehicle/CMG system became saturated. The vehicle was controlled by TACS only if selected, or if the CMG system was incapable of adequately controlling the vehicle.

TACS was used to control the attitude of the vehicle during the following events:

- Separation of the S-II stage from the SWS
- Maneuver to gravity gradient for PS jettison
- PS jettison
- ATM deployment
- Maneuver to and hold SI attitude prior to CMG spinup
- ATM and OWS solar array deployment
- CMG spinup

The TACS augmented the CMG Control Subsystem as previously described during:

- Docking and undocking of the CSM(s)
- Reacquisition of and holding the SI attitude
- SWS/CMG momentum desaturation
- Z-LV mode

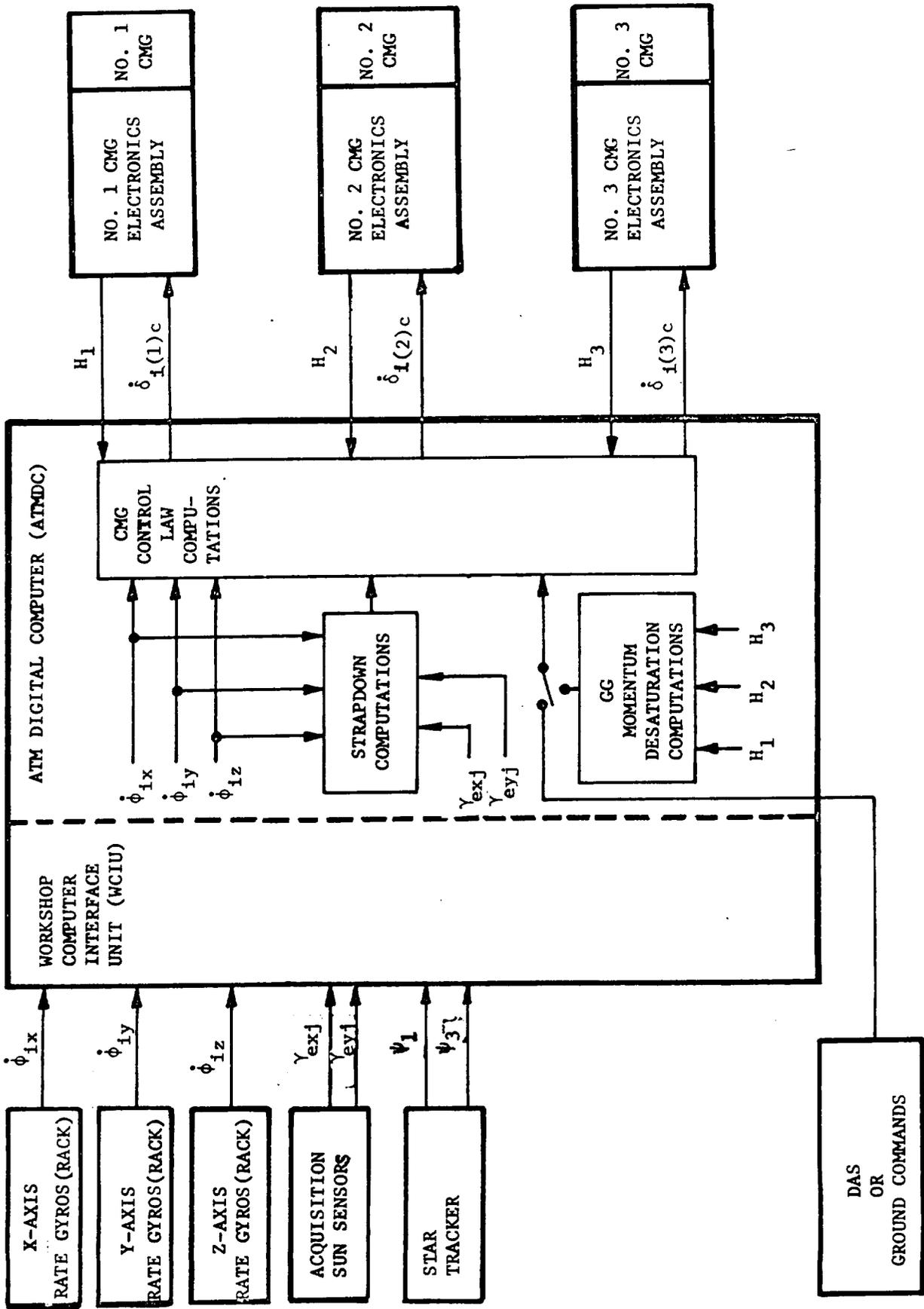


Figure II.J-5 Control Moment Gyro Control System Block Diagram

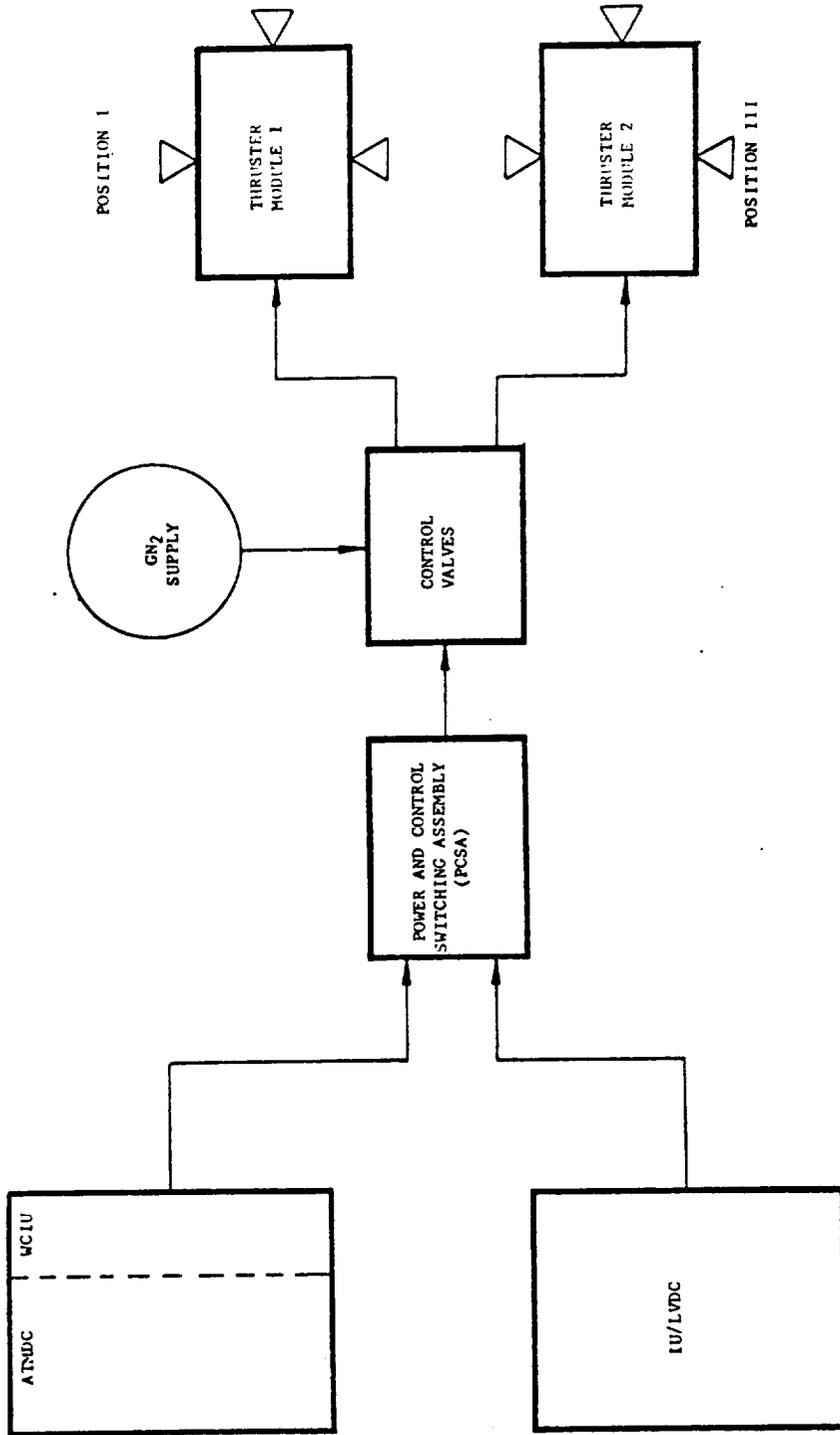


Figure II.J-6 TACS Functional Operation Block Diagram

The TACS utilized six cold gas GN₂ thrusters located on the aft skirt of the OWS, as shown in Figure II.J-7. Table II.J-5 lists the torques that these thrusters provided.

Table II.J-5. Vehicle Axes Torques

<u>THRUSTER</u>	<u>X-AXIS TORQUE</u>	<u>Y-AXIS TORQUE</u>	<u>Z-AXIS TORQUE</u>
1	-	Negative	-
2	Negative	-	Negative
3	Positive	-	Positive
4	-	Positive	-
5	Positive	-	Negative
6	Negative	-	Positive

Each thruster force varied from approximately 100 pounds (force) at the beginning of the mission and diminished to approximately 10 pounds (force) at the end of the mission. To compensate for this, the Minimum Impulse Bit (MIB) firing time (40 to 400 milliseconds) was changed via astronaut/ground command.

The TACS firing logic, based on a control law, was designed to null out the attitude error and rate error simultaneously. Figure II.J-8 is an uncoupled phase plane representation of the TACS switching lines.

From its inception, basic hardware design of the TACS was changed very little. However, numerous software changes occurred in the TACS control law constraints, i.e., attitude gains (a_{0i}), rate gains (a_{1i}), rate ledge limits, etc., in order to utilize the TACS in the most efficient manner as an integral part of the APCS.

(3) EPC Subsystem. The experiment package and EPC sensors were mounted to a three-degree-of-freedom spar as shown in Figure II.J-9, that is contained in the ATM Rack. The flex pivots allowed approximately ± 2 degrees of rotation about the X_{EPC} and Y_{EPC} axes. Rotation about the Z_{EPC} axis over a range of ± 120 degrees was obtained. Solar North Pole was the experiment zero reference position for roll.

The EPC Subsystem was used to maintain attitude control of the spar, and thereby, the experiment package. The package was provided with an independent control system to essentially isolate it from perturbations due to large disturbance torques on the vehicle, e.g., torques created by crew motion. A simplified block diagram of the subsystem is shown in Figure II.J-10.

The EPC provided automatic control of the experiment package X_{EPC} and Y_{EPC} axes. Manual positioning of the two axes was also provided for the purpose of offset pointing the experiment package. The FSS was used for sensing spar attitude errors with rate gyros sensing rates. The Experiment Pointing Electronics Assembly (EPEA) conditioned the

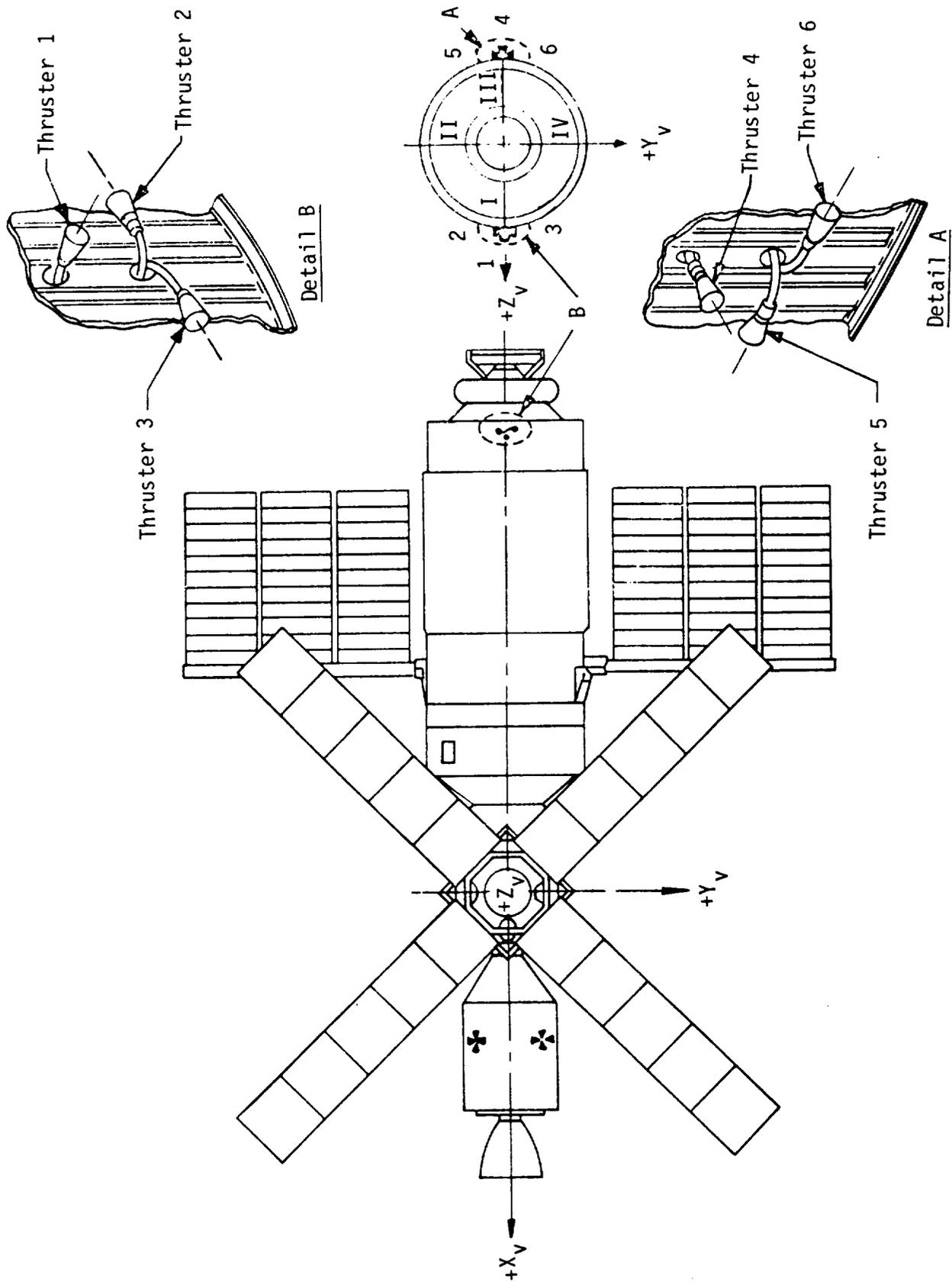
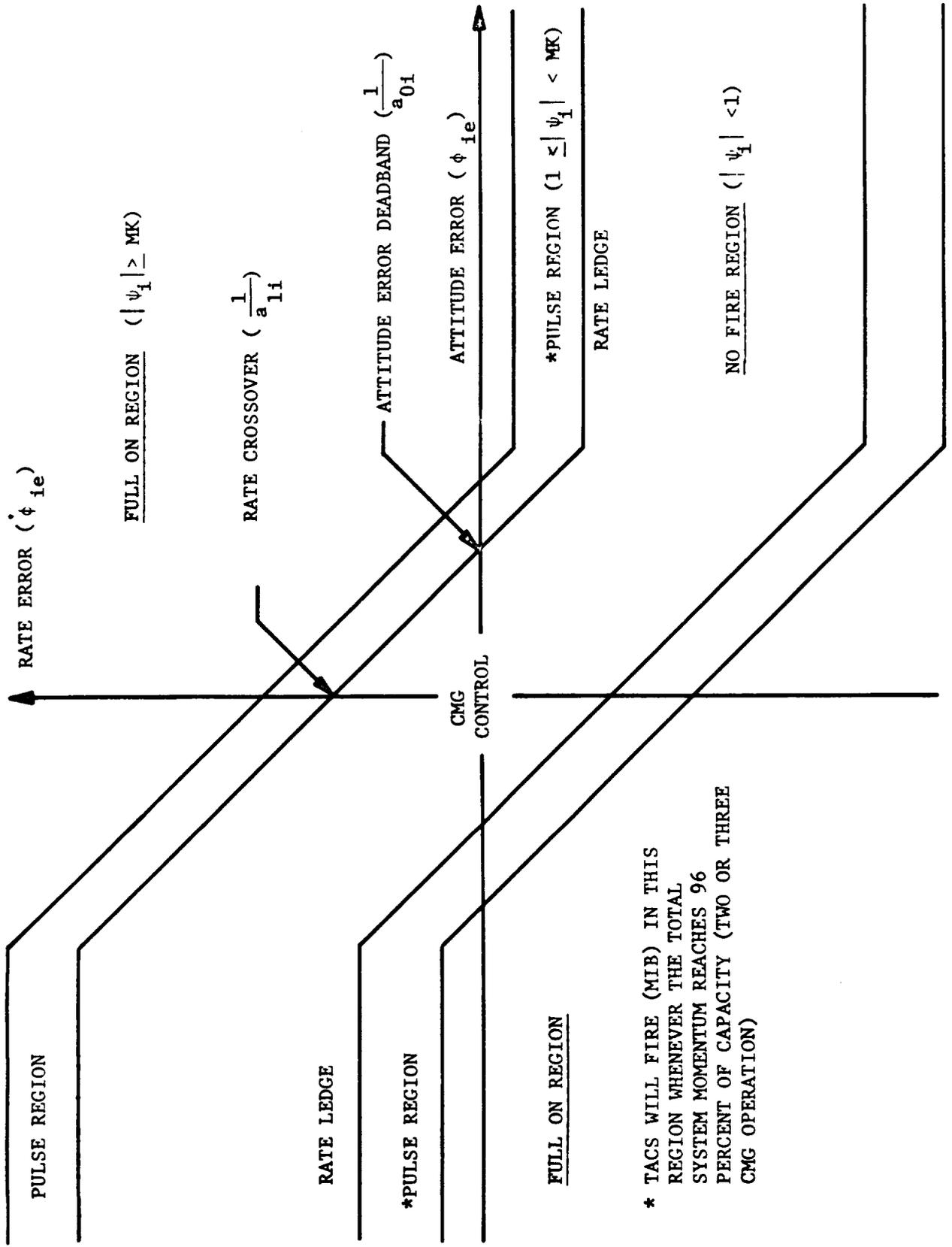


Figure II.J-7 TACS Configuration



* TACS WILL FIRE (MIB) IN THIS REGION WHENEVER THE TOTAL SYSTEM MOMENTUM REACHES 96 PERCENT OF CAPACITY (TWO OR THREE CMG OPERATION)

Figure II.J-8 Uncoupled Phase Plane Diagram

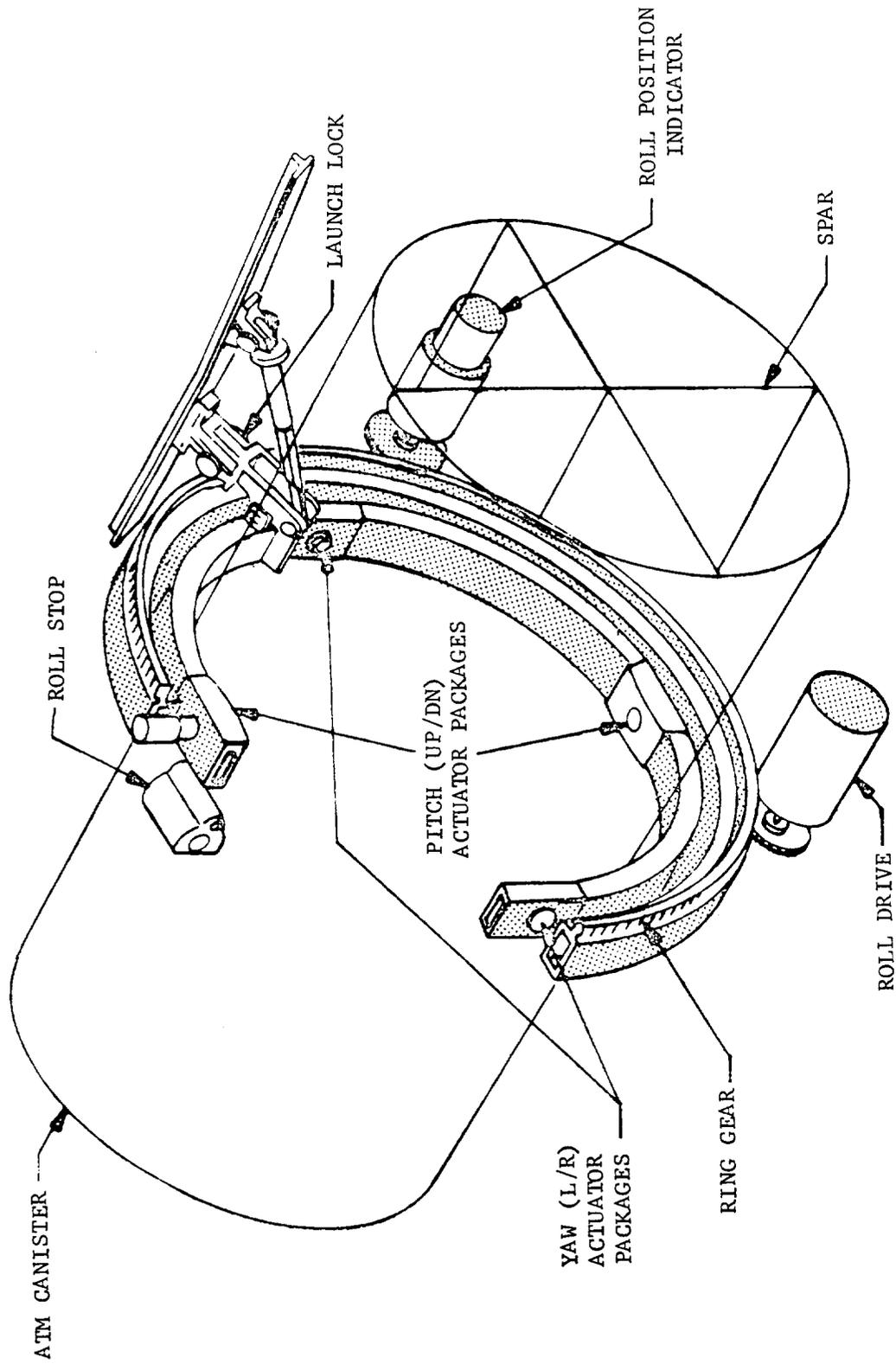


Figure II.J-9 ATM Solar Experiment Pointing Mechanism

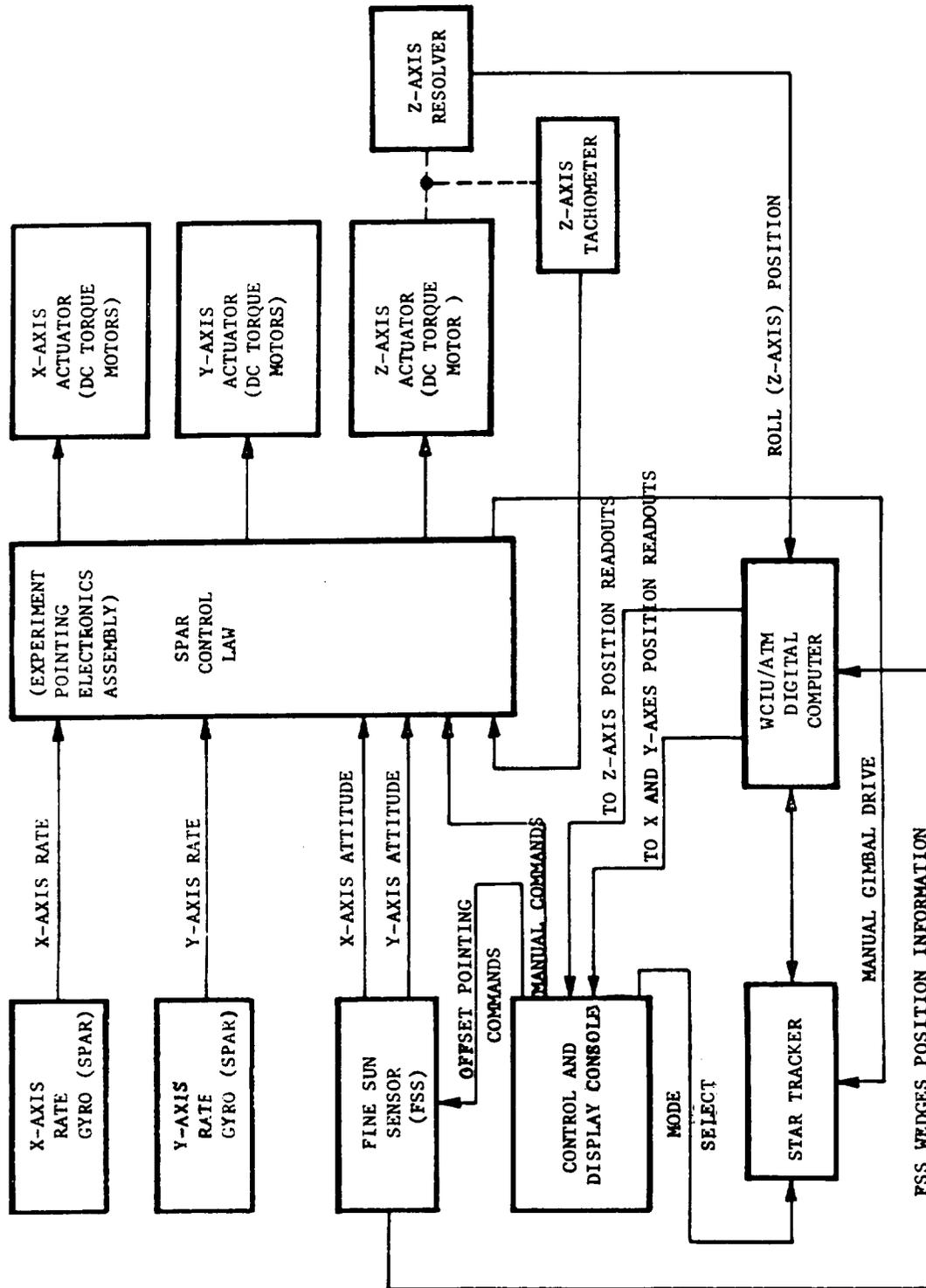


Figure II.J-10 Experiment Pointing and Control Subsystem Block Diagram

sensors signals to provide rate plus displacement command signals to the flex pivots actuators (DC torque motors).

The experiment package could be offset pointed in the X_{EPC} and Y_{EPC} axes over a range of ± 24 arc-minutes, with the center of the solar disk being the zero position. The solar disk measured approximately 32 arc-minutes from limb to limb. Offset pointing was accomplished by positioning an optical wedge located in each channel of the FSS. The wedge was mounted in the path of the sunlight passing through the FSS optics, and could be rotated to refract the sunlight a fixed angle in a controlled direction. The wedges were positioned by a drive mechanism controlled by the astronaut via the Manual Pointing Controller. A wedge offset produced a FSS output error voltage that causes the spar to rotate about the appropriate axis (X_{EPC} or Y_{EPC}) and point the FSS, and thereby the experiment package, in a direction that would drive the FSS output voltage to null. Stability was then automatically maintained by the EPC Subsystem. The solar experiments were aligned to the FSS. The position of each FSS wedge was displayed on the ATM C&D Console, and corresponded to the experiment package offset position from the center of the sun in the X_{EPC} or Y_{EPC} axis.

The RPM was used to rotate the spar about the Z_{EPC} axis over a range of ± 120 degrees. The mechanism was commanded by the astronaut via rate switches of the Manual Pointing Control Panel located on the C&D Console. Spar roll rates of ± 7 , ± 3.5 , ± 0.7 , and ± 0.35 degrees per second could be commanded. Once the spar was positioned, the RPM would hold the location until a repositioning command was received. The astronaut repositioned the spar in accordance with experiment demand requirements. The astronaut could also utilize the ATM EVA Rotation Control Panel (during extravehicular activity) to command rates of $\pm 7/3.5$ or $\pm 0.7/0.35$ degrees per second to reposition the spar. The rates were dependent on the setting of the Manual Pointing Roll Gain switch on the ATM C&D Console. The spar roll position was displayed on the Console.

c. CMG Control Law Development. The three double-gimbal CMGs imparted a reaction moment to the vehicle as a function of their actual relative gimbal rates. The six CMG relative gimbal rates had to be commanded from information derived from body-mounted attitude and rate sensors. Since these sensors were aligned to the vehicle geometric axes, they provided information relative to these axes only. This three dimensional information had to be routed or "steered" to provide six commanded CMG gimbal rates which would produce a reaction moment to optimally cancel any disturbance moment. The law that governed this generation of a six dimensional vector based upon three axes information was called the steering law.

The first control law under investigation was deficient in that for some regions of CMG gimbal angles, the primary axes moments were reduced but the cross-coupling moments were increased significantly. One of these regions was when all inner gimbals were zero and all outer gimbals were minus 45 degrees.

The Cross-Product Steering Law was offered by MSFC as an alternative to the Langley Control Law. To nullify a disturbance torque, the H-vector of each CMG was made to move into the direction of the disturbance torque. While both of these laws basically were designed to do this, the Cross-Product Law included the sine functions of the inner gimbal angles to reduce the cross-coupling effects. If used directly to control the CMG cluster, the steering law would fall short of the control goal, an invariant forward gain with a minimization of cross-coupling torques.

The "H-vector control law" which was developed was a closed loop controller. This law, when used with the Cross-Product Steering Law, provided an almost optimal CMG cluster control law. The ideal control law implied that the torque obtained from the CMG cluster must be identical with the commanded torque to the CMG cluster. The H-vector Control Law scales an $\bar{\alpha}$ vector to be a commanded torque. The $\bar{\alpha}$ vector was based on vehicle body sensor information and thus indicated the direction of the disturbance moment. The commanded torque vector was then electronically integrated and compared to the angular momentum of the CMG cluster. The error momentum vector was then nulled by driving the six CMG gimbal angles with the aid of the steering law.

Using the H-vector control law and its associated Cross-Product Steering Law, the CMG gimbal angles required to produce a given total momentum vector were not uniquely defined. A highly undesirable momentum distribution could develop where two of the three individual angular momentum vectors were parallel and the third was antiparallel. For this antiparallel orientation, the CMG cluster exhibited zero gain along the axis of colinearity. Thus, even though the CMGs were not saturated they would not be able to compensate for a disturbance along that axis. Studies were then started on the development of an "Isogonal Distribution and Rotation Law."

H. Kennel (MSFC) had shown (January 1968) that for any given total angular momentum vector, it was desirable to place the three individual spin vectors into an orientation in which each contributed an equal component along the total vector. This constraint resulted in equal angles between the actual vectors and the total, i.e., an isogonal distribution. The H-vector control law utilized only three of the available six degrees of freedom; the isogonal distribution used two of the remaining three degree of freedom. Rotation of the individual angular momentum vectors about the total angular momentum used the remaining degree of freedom. This Rotation Law minimized impact of the CMGs inner gimbal stops. The Isogonal Distribution and Rotation Law not only eliminated any antiparallel condition, but also extended the bandwidth of the direct gain and reduced the cross-coupling torque.

Further development by MSFC (H. Kennel) of the CMG Control Law was obtained in July 1970. The control law was divided into three portions: the steering law (no cross-coupling), the distribution law, and the rotation law. The steering law generated gimbal rate commands such that

the torques resulting on the vehicle were identical to the desired torques in direction and magnitude. This assumed that the actual gimbal rates were identical to the commanded gimbal rates. Only when the gimbal rate capability was exceeded would the magnitude of the resulting torque be less, but the direction would remain that of the command. The distribution law tended to spread the CMG angular momentum vectors away from each other, and the rotation law minimized gimbal stop impact.

(1) Steering Law. The steering law was noncross-coupling in the sense that the actual torque on the vehicle was equal to the commanded torque (normalized) under the condition that the commanded and actual gimbal rates were equal. This law used vector pairing exclusively: CMGs No. 1 and No. 2 formed pair A, CMGs No. 2 and No. 3 formed pair B, and CMGs No. 3 and No. 1 formed pair C. Each CMG was therefore participating in two pairs, and the resulting angular velocity commands were added later. Since pairing was used, the individual sums and the cross products had to be generated, along with their magnitudes (or their squares) used for normalization. An extremely small positive quantity was added to the magnitudes to avoid a division by zero. Each vector pair could generate a control torque, and the demand on each pair was scaled according to the individual ability while keeping the total to unity. Each vector pair assumed its share of the command by dividing it into a component along with another perpendicular to their sum. The first was handled by a scissoring action of the two CMG vectors with respect to each other and the second by a rotation of the pair as a unit. The appropriate angular velocity commands could then be generated. The steering law assumed that all CMG momentum magnitudes were equal to the nominal. It is noted that the angular velocity commands of the steering law are not, in general, perpendicular to the CMGs, and do not depend on the CMG mounting configuration. However, the mounting configuration determined the transformation of the CMG angular velocity commands into gimbal rate commands.

(2) Distribution Law. Most of the CMG momentum change was along the orbit normal, disregarding maneuvers. The distribution law attempted to make the components of the CMG vectors along the orbit normal equal to each other. This resulted in spreading the vectors far apart, reducing the angular velocity required of the vectors to meet the required momentum change. The angular velocity commands were later generated in conjunction with the ones from the rotation law. The distribution was made by rotations about vector pair sums which did not affect the total momentum, i.e., no torques resulted on the vehicle. For two CMG operation there was no distribution possible, and the distribution gain was set to zero.

(3) Rotation Law. The rotation law utilized only rotations about vector sums, and the total angular momentum was not disturbed. The angular velocities for the rotations were generated such that the largest gimbal angles were reduced, thus minimizing gimbal stop impact.

By early 1971, the CMG Control Law was divided into two parts: the steering law and the rotation law. The distribution law above was combined into the steering law. This control law was the flight configuration.

d. Momentum Management. Since CMG saturation was caused by noncyclic disturbance torques, predominantly gravity gradient and aerodynamic drag, a way had to be devised to eliminate or at least minimize these torques with the least expenditure of fuel. With the given vehicle configuration and mission requirements of pointing the vehicle Z-axis at the radiometric center of the sun every daylight period, it was only possible to minimize, not eliminate, these noncyclic torques. The problem was approached in two ways.

- Minimize the noncyclic disturbance torques by finding an optimal vehicle orientation but maintaining the vehicle Z-axis pointed towards the center of the solar disk. Investigations resulted in the orbital plane update and pseudo minimum principal axis of inertia schemes. The latter technique sampled vehicle momentum at specified times during the daylight orbital period and compared it with the previous days samples. The compared samples indicated whether the bias momentum components about the vehicle axes were increasing or decreasing. This information was then translated into appropriate angle position commands about the vehicle Z-axis to ensure a minimum bias momentum accumulation.
- The saturation effects of the remaining noncyclic disturbance torques were nullified by periodically producing controlled bias torques which would tend to desaturate the CMG cluster momentum buildup.

For the latter approach, early studies (1968-1969) analyzed the behavior of gravity gradient desaturation techniques for the LM/ATM/CSM backup vehicle configuration using complex vehicle maneuvers.

The basic momentum management strategy that evolved consisted of maneuvering the vehicle during the dark portion of the orbit in order to develop gravity gradient torques which reversed the rate of change of angular momentum, thus causing desaturation. The vehicle maneuvers that yielded such a momentum behavior were based upon analytical expressions of the gravity gradient torques acting on the vehicle in an arbitrary orientation. The gravity gradient torques were primarily functions of the vehicle moments of inertia, orbital position, and orientation of the mass distribution with respect to the gravity potential.

For the SI orientation the maximum momentum buildup occurred on the vehicle X_V axis since the torque about this axis never changed sign over an orbit. On the other hand, the integral value of the Y_V or Z_V axis torque was zero since both were perfectly cyclic with no bias. The

X_v axis bias torque was primarily a function of the angle between the orbital plane and the solar oriented vector. A large angular maneuver about this axis could reverse the bias torque and effect momentum desaturation. Residual momentum resulting from aerodynamic torques and the lack of perfect desaturation due to finite vehicle maneuver times was regulated by commanding small rotations about the other orthogonal vehicle axes. An added advantage of such a simple scheme was that it was not necessary to explicitly monitor the vehicle orientation. That is, additional sensors and peripheral computation were not necessary to demaneuver in order to be solar oriented at the sunrise terminator.

This approach to the problem resulted in the study of a large class of control laws employing sample data schemes. The basic control laws were first implemented and subsequent modifications were the result of the addition of aerodynamic torques. The effectiveness of each technique was determined simply by the ability to constrain the accumulated momentum to some average value. In the case of the most general desaturation technique, momentum buildup was controlled using as little as 39 percent of the orbital plane for desaturation maneuvers for an orbital to ecliptic plane inclination of 45 degrees.

The addition of aerodynamic torques from a preliminary aerodynamic model yielded an environment in which momentum control was more difficult. This required the design of more efficient control laws of the same general type. Control was achieved in all cases for an orbital desaturation of 50 percent. The subsequent addition of more realistic aerodynamic characteristics rendered most of the control methods ineffective. Only the most general form of the given class of laws yielded partial but unsatisfactory control in the combined gravity and aerodynamic environment. Thus, the revision of the aerodynamic portion of the model necessitated the development of an entirely new control policy. This control policy consisted of performing large angular maneuvers about two vehicle axes and subsequent small angle maneuvers about three vehicle axes in such a manner as to track the gravity vector on the dark side of the orbit. This method approached optimality in terms of gravity gradient desaturation, i.e., momentum buildup was controlled using as little as 25 percent of the orbital plane for desaturation maneuvers for a worst case orbital-to-ecliptic-plane inclination of 45 degrees.

In the simulation studies, a great deal of information was obtained concerning the type of control policy required as well as information on vehicle behavior. This was important for future studies which included the implementation of new control methods, variation of orbital parameters, changes in the required desaturation percentage, and inclusion of other external torque disturbances.

From the above studies, and additional analyses, the feasibility of using the gradient of the gravity field to desaturate the CMG subsystem by means of small-angle vehicle maneuvers was established. Three successive maneuvers, under ATMDC control, were performed during the night portion of the orbit for CMG desaturation.

6. Design Verification

a. Analysis

(1) General Description. Extensive analysis were performed to verify compliance of APCS performance with requirements and goals. The performance analysis covered three principle topics:

- Activation
- Normal Operation
- Contingencies

Of these, most work was performed on analysis of normal operations which was further categorized as:

- Rendezvous and docking
- Maneuvering
- Experiment operation
- Navigation, timing, and attitude control

For each of the general topics analyzed, i.e, activation, normal operation, contingencies, the analysis addressed the following specific topics:

- Disturbances
- Transition events
- Sensor characteristics
- Computer software
- Actuator characteristics
- Vehicle properties

(2) Activation Analysis and Documentation. Analysis was performed and documented verifying capability of APCS performance for each of the following activation events:

- Deployment sequence
- Control following orbit insertion
- Payload shroud jettison
- Maneuver to SI
- Transfer control of IU to ATM
- Propellant usage under IU control
- Control with partially spunup CMG

(3) Normal Operation Analysis Documentation. Analysis was performed and documented to demonstrate and verify APCS capability for meeting performance requirements. These analyses addressed the following subjects:

(a) Rendezvous and docking. Response during axial docking, TACS control for undocked configuration; control via CSM for the docked configuration.

(b) Maneuvers. Pointing and maneuvering capabilities analysis, maneuvering from rendezvous Z-LV attitude to SI, TACS impulse requirements for Z-LV maneuvers, TACS impulse requirements for Z-LV with desaturation maneuvers inhibited.

(c) Experiment Operation. Analysis was performed to determine capability of the APCS for meeting pointing and stability requirements of ATM experiments, EREP experiments, and various experiments concerned with stellar and solar pointing which are mounted in the OWS scientific airlock. In particular, these analyses addressed the following:

- Total error sources of EREP pointing.
- Total error budgets for CMG/EPC pointing.
- Stability and response of EPC system.
- Stellar pointing; errors due to strapdown calculations and maneuver accuracy.
- CMG outer loop control compensation.
- CMG hardware effects.
- CMG/TACS impulse budgets.
- CMG/TACS flexible body interaction.
- EPC/CMG-vehicle coupling.
- EPC control-experiment dynamics interaction.
- EPC control-compensation and stability design.

(d) Navigation and Timing. Various analyses and simulation studies were performed and documented to verify maintenance of the vehicle attitude reference frame. These documents dealt specifically with:

- Strapdown attitude reference frequency and time response.
- Navigation and timing computation scheme.
- Navigation algorithm.
- Star tracker control.
- External disturbance torques reset logic.

(4) Results. The results of all analysis led to many APCS design and operational conceptual and implementation changes as the program progressed from initiation through SL-4. In summary, every aspect of the APCS operation was thoroughly analyzed to achieve design verification prior to operation. More detailed accounts and description of analyses performed can be obtained from the APCS Summary Document; 50M78002, January 31, 1973.

b. Tests. Flight hardware testing of the ATM module during Post-Manufacturing Checkout, Thermal Vacuum, KSC, etc., is beyond the scope of this section, but is covered in ED-2002-1416 "Skylab System Verification Analysis and Pointing Control System." Hardware simulation and software verification defined herein is restricted to those activities utilizing the ATMDC flight program in closed-loop operation with dynamic models and/or flight type hardware.

Three independent simulators were used in performing hardware simulation and software verification. The System 360 Model 75, located at IBM - Huntsville is an all digital software simulator which modeled both the vehicle and the ATMDC. The System 360 Model 44, located at IBM - Huntsville, incorporated a flight type ATMDC with software models of the Workshop Computer Interface Unit (WCIU) and the vehicle. The Hardware Simulation Laboratory (HSL), located at MSFC, was an all hardware simulation with the exception of software equations for vehicle body dynamics and software simulation of the OWS TACS. The HSL had the capability of substituting software models for all sensors and actuators with the exception of the ATMDC. The functions performed by the simulators were software verification, system integration and dynamic responses. These functions were investigated for the activation, normal, and contingency operational modes.

The two periods under test during activation were ATM deployment and CMGs/TACS activation.

For normal APCS operation the following areas were investigated and verified:

- (1) Rendezvous and Docking
 - Z-LV(R) Maneuver Generation
- (2) Maneuvers
 - Maneuver Generation
 - Momentum Desaturation Maneuvers
 - Attitude Hold Maneuvers
 - Z-LV(E) Maneuvers
- (3) Experiment Operation
 - EPCS Interfaces
 - Roll Reference Validation
 - SI Offset Pointing
 - EPCS Responses
- (4) Navigation, Timing, and Attitude Control
 - Navigation and Timing
 - Attitude Reference Generation
 - Sensor Data Processing
 - CMG Control
 - TACS Control

Various off-nominal, unusual, and emergency situations were investigated to evaluate their effects and included:

- Redundancy Management - CMG
- Redundancy Management - Rate Gyro
- Redundancy Management - Acq. SS
- ATMDC Self-Test and Switchover
- 8K Program
- Random Reacquisition

7. Conclusions and Recommendations. As has been shown, the design, fabrication and assembly, along with the concomitant analysis, simulations, test and checkout of the APCS has encompassed a time span of seven years, i.e., from approximately June 1966 to the launch of Skylab 1 on 14 May 1973. During this period, an exhaustive effort was made not only to ensure the adequacy of the basic control system for the early mission objectives, but to comply with new system requirements as a result of evolving mission objectives.

The design of the original PCS rendered it quite flexible to implementation of new design changes. Primary vehicle control with the use of CMGs, and fine pointing and stabilization of the solar experiments via the EPCS did not change from the original design concepts. The transition from WWS to DWS included computation of the CMG control laws and momentum management in a digital fashion as opposed to analog techniques in the former configuration. The extended mission duration caused a concerted look towards increasing reliability with the addition of backup hardware and insuring the probability of mission success. Even the addition of the Z-axis pointing local vertical requirement did not impose any severe restrictions on the APCS to perform this operation. Mechanization of the hardware and implementation of the required software proved readily attainable by early judicious planning of a flexible control system design.

A great deal of time and effort was expended in deriving and integrating a fairly complex control system to obtain pointing accuracies in the few arc-second range. Because of its inherent design flexibility, only minimal modifications to the APCS backup hardware would be required to render it a viable and low cost payload candidate for future manned space missions.

K. Contamination

Since contamination does not fall into a specific category as a spacecraft system, such as electrical power systems or thermal control and environmental control systems, an explicit systems definition of contamination cannot be discretely established. The systems definition for Skylab is a description of spacecraft contamination, definition of the sources and their characteristics, and the measures and controls that were established so that contamination would not compromise the Skylab mission objectives.

As a result of manned spacecraft's outgassing from exposed non-metallic surfaces, leakage characteristics, controlled engine firings, venting waste materials, and other necessary vents, an induced atmosphere around the spacecraft existed and was dependent upon the ambient orbital conditions and the nature of the contaminant. This induced atmosphere was capable of generating an optical interference background through particulate scattering, broadband and selective band absorption, and radiating in the infrared. The induced atmosphere also provided a source of contaminants that were deposited upon critical experimental or operational surfaces in the form of thin films or particulate matter. The specific form of contamination and its subsequent nature of degradation was a complex function and was dependent upon the spectral characteristics of specific instruments, instrument design, and operational usage.

1. Design Requirements. The contamination control for Skylab came as a result of basic Skylab documentation such as the Cluster Requirements Specification, RS003M00003, which gave the technical requirements. A special chartered group at the Marshall Space Flight Center, the Contamination Control Working Group (CCWG), was assigned to identify sources and sensitive elements, eliminate sources through hardware modifications, approve actions and resolve problems that arose regarding design, testing, etc.

The CRS established the prelaunch cleanliness requirements for manufacturing transportation and stowage, and contamination control plans for ground handling and cleanliness at KSC. The launch and/or orbit control requirements set forth the allowable degradations due to contamination on thermal control surfaces, cluster windows, optical experiments and instruments and solar cell panels, cluster design for contamination control such as assembly, geometry, or line-of-sight considerations; locations of sensitive elements protective shields and covers; material selection; and material outgassing control. In addition, the CRS established design for contamination tolerances, orbital venting and dumping, leakage, operational controls, and timelining of orbital operations.

However, the requirements imposed by the CRS became effective after assembly of the cluster, and continued through the launch and

C-4

orbit phases. Contamination control of modules and experiments during design, manufacturing, test, and delivery phases was governed by the contamination control plan in the respective specifications that were written with the cognizance of CRS requirements.

The CCWG was formed in December 1970 to formulate and coordinate the technical efforts of MSFC for implementation of CRS requirements stated above. In particular, this group was responsible for the following tasks:

a. Assuring identification, coordination and implementation of optical contamination orbital control requirements and constraints;

b. Assuring necessary overall coordinations to properly develop requirements for (accomplishment of) orbital optical environment through the definition and resolution of problems associated with;

- Selection of materials of construction,
- Orbital vent locations,
- Scheduling of certain mission events such as docking activities and venting,
- Attitude control thruster selection, location, and firing,
- Ordnance and pyrotechnic devices,
- EVA activities,
- Ground assembly, test, and handling,
- Manufacturing operations.

c. Resolving problems and initiating actions regarding design, analysis, study, test and operations by employing the line organizations of MSFC or of various contractors.

The CCWG accordingly supported development of analytical models and a series of extensive ground test programs to verify the models and to prove the efficacy of many control measures implemented with respect to flight hardware. As a result of these activities, analytical capability existed so that direct mission support of Skylab could be performed by predicting and verifying through flight data Skylab environments, establishing constraints or controls, assessing anomalies, and preparing a section of the Mission Evaluation Report of Skylab with respect to contamination. In addition, the CCWG was effective in eliminating vents, rerouting vents for minimum impact, establishing filters, and recommending many changes to minimize effects of contamination on Skylab. Many materials were subjected to tighter controls by virtue of the CCWG actions.

2. Functional Description

a. Contamination Sources. The various contamination producing sources of the Skylab Cluster were assessed and the nature and characteristics of these sources were established. The primary sources

of concern were those effective during the boost and orbital phases of the mission. The major sources are:

- Outgassing of vacuum exposed materials;
- Venting of liquids and gases;
- Cabin atmosphere leakage;
- Motor exhaust contaminants;
- Extra vehicular activity;
- Sloughing of particles from external surfaces.

Of these, the primary sources of contamination are outgassing, venting of liquids and gases, leakage, motor exhaust products, and particle sloughing. Quantitative evaluation of particle sloughing was not made before the mission because of their unpredictability.

(1) Outgassing of Vacuum Exposed Materials. The total cluster nonmetallic area exposed to vacuum was approximately 250,000 ft². The average cluster steady-state outgassing rate was 20 grams/day assuming an average rate of 10⁻¹⁰ grams/cm²-sec (based upon material outgassing requirements as set forth in 50M02442). There were approximately 195 different nonmetallic vacuum-exposed materials with surface areas larger than 1 square foot on the Skylab cluster.

The outgassing rate for a given material is a function of pre-treatment, thickness, temperature, and age. Since the outgassing rate is primarily a function of temperature and age, and since the temperature is a function of orbital positions, the actual outgassing rate of a particular surface is a continuously varying function of time.

(2) Venting of Liquids and Gases. The venting of liquids and gases was also a major source of contamination during Skylab orbital operations. Since venting activities were basically controlled or preplanned activities, these sources and their impact could be controlled to a degree by establishing mission rules and constraints to minimize their impact. The locations, directions, mass flow rates, mass distributions, operational frequency and duration, and constituents were established for each of the vents on the GSM, MDA, IU, AM, and OWS. The vent locations are shown in Figures II.K-1 and II.K-2 and Table II.K-1. The vent characteristics are shown in Table II.K-2.

(3) Cabin Atmosphere Leakage. The maximum specified cluster leakage was 14.7 lb/day, however, the average leakage observed was approximately 3.75 lb/day. The leakage products were mostly light gases, O₂, N₂, CO₂, H₂O, and were not expected to condense on critical surfaces.

(4) Motor Exhaust Contaminants. Three engine subsystems were operated in the vicinity of the Skylab Cluster. They were the Service Module Reaction Control System, Thruster Attitude Control System, and the Stage II Retrorockets.

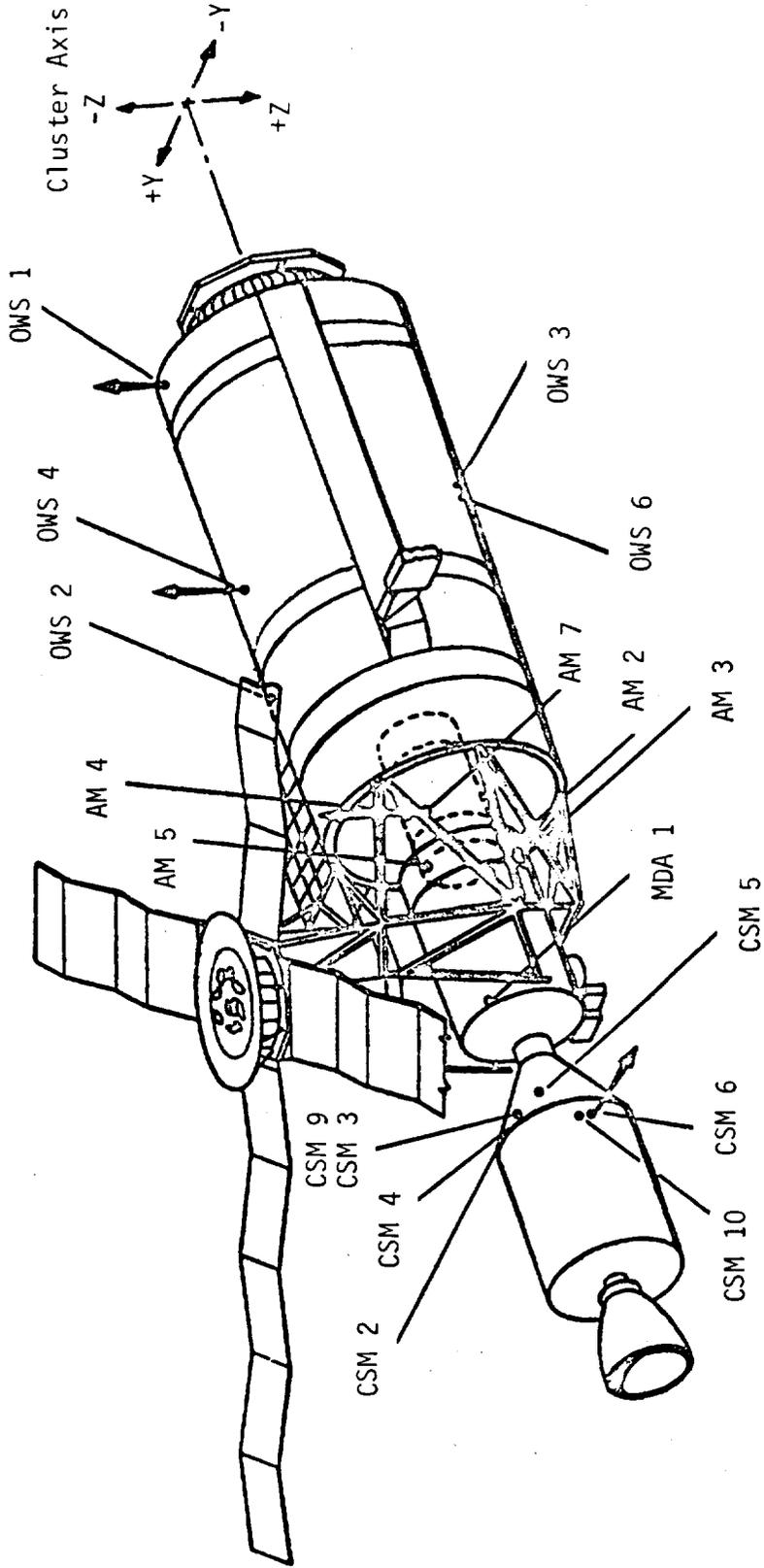


Figure II.K-1. Cluster Vent Locations (Top View)

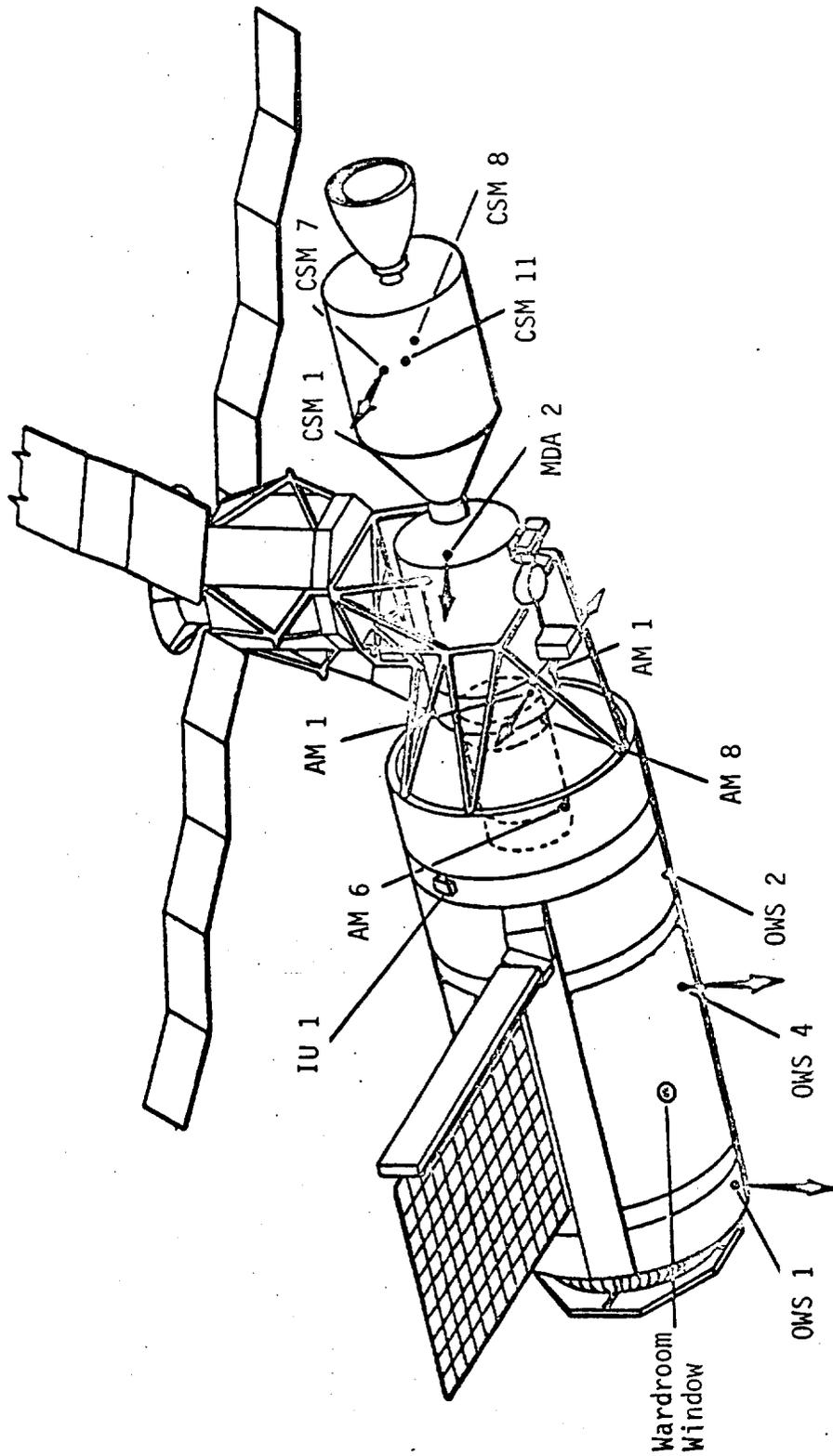


Figure II.K-2. Cluster Vent Locations (Bottom View)

Table II.K-1. Cluster Vent Locations

MODULE AND VENT	LOCATION			RADIAL (INCHES)	DIRECTION VECTOR
	STATION NUMBER	ANGULAR LOCATION (DEGREES)	ANGULAR LOCATION (DEGREES)		
<u>CSM</u>					
1 Stream Vent	3723.3	25.0 Off -Z toward +Y	-Z toward +Y	64	60° Off -X See Ang Location
2 Urine Vent	3734.6	16.5 Off -Z toward +Y	-Z toward +Y	72	60° Off -X See Ang Location
3 Auxiliary Urine Vent	3703.3	24.0 Off -Z toward -Y	-Z toward -Y	42	60° Off -X See Ang Location
4 Waste Water Vent	3738.1	6.0 Off -Z toward +Y	-Z toward +Y	74	60° Off -X See Ang Location
5 Air Vent	3725.3	34.5 Off -Y toward -Z	-Y toward -Z	65	60° Off -X See Ang Location
6 H ₂ Purge Vent	3764.2	4.0 Off -Y toward +Z	-Y toward +Z	78	Radial
7 O ₂ Purge Vent	3813.4	5.0 Off +Y toward -Z	+Y toward -Z	78	Radial
8 Fuel Cell H ₂ Cryo Dump	3880.0	72 Off +Z toward +Y	+Z toward +Y	78	Radial
9 Fuel Cell O ₂ Cryo Dump	3703.0	24 Off -Z toward -Y	-Z toward -Y	42	60° Off -X See Ang Location
10 Fuel Cell H ₂ Cryo Relief	3763.0	5 Off -Y toward -Z	-Y toward -Z	78	Radial
11 Fuel Cell O ₂ Cryo Relief	3832.0	81 Off +Z toward +Y	+Z toward +Y	78	Radial
<u>MDA</u>					
1 Vacuum Vent	3606.5	45 Off -Z toward -Y	-Z toward -Y	63	Radial
		30 Off +Y toward +Z	+Y toward +Z	63	Radial
2 Experiment Vent	3613.3	30 Off +Y toward -Z	+Y toward -Z	46	30° Off Y-Z Plane Toward -X
<u>IU</u>					
1 Sublimator Vent	3248	60 Off -Z toward +Y	-Z toward +Y	120	N/A - Vents Internal IU; Leaks Out Meteoroid Curtain
<u>AM</u>					
1 Molecular Sieve (2)	3433.3	Y ± 30 in. Z-72.5 in.	-Z toward +Y	-	+ Y
2 Primary Condensate Vent	3399.0	49.0 Off +Z toward -Y	+Z toward -Y	63	Radial
3 Secondary Condensate Vent	3399.0	26.5 Off +Z toward -Y	+Z toward -Y	63	Radial
4 EVA Depressurization Vent	3295.5	8.0 Off -Z toward +Y	-Z toward +Y	33	Radial
5 Nitrogen Vent	3394.8	On -Z	-Z	63	Radial
6 Aft Overpressure Vent	3253.8	10.0 Off +Z toward -Y	+Z toward -Y	33	Radial
7 Airlock Overpressure Vent	3351.8	30.0 Off -Z toward -Y	-Z toward -Y	33	Radial
8 Forward Overpressure Vent	3386.8	10.0 Off +Z toward -Y	+Z toward -Y	33	Radial
<u>OVS</u>					
1 Waste Tank NPV (2)	2780.3	18.2 Off +Z toward +Y	+Z toward +Y	130	Radial
2 Habitation Area NPV (2)	3165.6	25.0 Off +Z toward +Y	+Z toward +Y	130	Radial
3 Experiment M092/M171 Vent	2966.7	40.0 Off +Z toward -Y	+Z toward -Y	130	Radial
4 Scientific Airlocks (2)	3026.8	0.15 Off -Z toward -Y	-Z toward -Y	130	Radial
		1.9 Off +Z toward -Y	+Z toward -Y	130	Radial
5 Pneumatic Bottle Vent	3191.9	43.0 Off -Z toward +Y	-Z toward +Y	65	Radial
6 Experiment M171 Vent	2966.1	31.0 Off +Z toward -Y	+Z toward -Y	130	Radial

Table II.E-2. Skylab Vent Characteristics

MODULE AND VENT	TH	CONTROL RESPON.	FREQUENCY	DURATION	MASS FLOW RATE	CONSTITUENTS	PLUME SHAPE FUNCTION	
CSH	Steam vent	No	Contingency	TBD flight data	TBD flight data	H ₂ O vapor	CO ₂ [?]	
	Urine vent	No	Contingency	TBD flight data	TBD flight data	Fecal bag gas; O ₂ ; frozen urine (85% w); urine vapor (15% w)	Undefined	
	Waste water vent	No	Contingency	TBD flight data	TBD flight data	Ice, H ₂ O vapor, H ₂ , KOH	Undefined	
	Air vent	No	1/mission	Continuous	TBD flight data	Silicone sealant, RTV, silica fiber	CO ₂ [?]	
	Fuel cell H ₂ purge	No	1/2 days for first 13 days	80 sec/cell (2 cells)	0.5 lb/hr	O ₂	CO ₂ [?]	
	Fuel cell O ₂ purge	No	1/4 days for first 13 days	120 sec/cell (2 cells)	TBD flight data (0.2 lb/hr max)	Li ₂	Undefined	
	Fuel cell H ₂ cryogen dump	No	Contingency	TBD flight data (45 min)	TBD flight data (1.0 lb/hr max)	LO ₂	Undefined	
	Fuel cell O ₂ cryogen dump	No	Contingency	TBD flight data	TBD flight data (6 lb/hr max)	H ₂	Undefined	
	Fuel cell O ₂ cryogen relief	No	Automatic	Contingency	TBD flight data	O ₂	Undefined	
	Fuel cell O ₂ cryogen relief	No	Automatic	Contingency	TBD flight data	O ₂	Undefined	
	Vacuum vents (2)	Yes	Ground	1/mission	9.5 minutes	1350 SCF/9.5 min each vent	H ₂	CO ₂ [?]
	Experiment vent	No	Crew	MS1 MS2 MS3 MS4 MS5 MS79	6.0 min (1 perf) 6.0 min (1 perf) 0.7 min (3 perf) 6.1 min (2 perf) 118 min (2 perf) 0.2 sec (each perf)	1.8 ft ³ G ₄ @ 5 psia in material	Scattered metals, metal vapors, exothermic gases	CO ₂ [?] CO ₂ [?] CO ₂ [?] CO ₂ [?] CO ₂ [?] CO ₂ [?]
Stabilator	No	None	Once-start first mission	7.5 hr vent + sublimation (~1000 hr)	4 lb/hr + 100 lb sublimation	Particulates, Gases 4.2 lb	CO ₂	
AM	Molecular sieve	Yes	1/28 days	15 hr/bed - 2 beds	Estimated at cycling rates X 0.1	CO ₂ , H ₂ O	CO ₂ [?]	
	Baleout	Yes	Continuous	Alternate beds; 15 minute cycles	H ₂ O 0.20 lb/hr av.; 5.2 lb/hr peak CO ₂ 0.25 lb/hr av.; 6.5 lb/hr peak H ₂ O ₂ 0.008 lb/hr av.; 2.1 lb/hr peak Estimated at 1.2 lb/min	H ₂ O vapor 0.071 lb/cycle CO ₂ 0.070 lb/cycle H ₂ O ₂ 0.022 lb/cycle Particulates H ₂ O vapor (15% w) ice particles (85% w)	CO ₂ [?]	
	Cycling	No	Contingency	TBD flight data	8.4 lb/min	Low apparent X B for detailed vent characteristics	Empirical	
	Primary condensate vent	No	1/EVA	30 sec	TBD flight data (23 to 456 lb/hr)	TBD flight data (360 lb/hr full flow)	N ₂	CO ₂
	Eva depressurization vent	No	Automatic	Contingency	TBD flight data	TBD flight data (360 lb/hr full flow)	O ₂ /N ₂	CO ₂
	Nitrogen vent	No	Automatic	Contingency	TBD flight data	TBD flight data (360 lb/hr full flow)	O ₂ /N ₂	CO ₂
	Aft overpressure vent	No	Automatic	Contingency	TBD flight data	TBD flight data (360 lb/hr full flow)	O ₂ /N ₂	CO ₂
	Airlock overpressure vent	No	Automatic	Contingency	TBD flight data	TBD flight data (360 lb/hr full flow)	O ₂ /N ₂	CO ₂
	Forward overpressure vent	No	Automatic	Contingency	TBD flight data	TBD flight data (360 lb/hr full flow)	O ₂ /N ₂	CO ₂
	Waste tank N ₂ P ₂ S (2)	Yes	Progr.	Once-start first mission	18 min.	20 lb/min av.	G ₄ (356 lb)	CO ₂ [?]
Waste processor	Yes	Crew	End each mission	5.5 minutes	2.1 lb/cycle	O ₂ /N ₂ (0.11 lb); H ₂ O vapor	CO ₂ [?]	
Waste management compartment dump	No	Crew	End each mission	100 min SL-2; 200 min SL-3, SL-4	2 lb/min nominal	Condensate (200 lb end SL-2; 400 lbs end SL-3, SL-4)	CO ₂ [?]	
Handroom system flushes	No	Crew	Start 1st mission	10.5 min	2 lb/min nominal	Biocide (21 lb)	CO ₂ [?]	
Waste processor	No	Crew	Start 2nd, 3rd mission	29 min	2 lb/min nominal	Biocide (58 lb)	CO ₂ [?]	
Squeeze bag dump (squeeze bag)	No	Crew	End each mission	13 min	0.1 lb/hr	H ₂ O vapor (0.6 lb/cycle)	CO ₂ [?]	
Urine dump	No	Crew	Nominal 4/day	6 hr nom.	2 lb/min nominal	H ₂ O (9 lb)	CO ₂ [?]	
Urine dump	No	Crew	1/3 days	4.5 min	2 lb/min nominal	Urine (3.2 lb) H ₂ O (1.9 lb) O ₂ /N ₂ (.02 lb)	CO ₂ [?]	
Initial blowdown	Yes	Programmed	Once-start first mission	30 min nom	44 lb/min nominal	SN 1338 lb	CO ₂ [?]	
Final blowdown	Yes	Ground	1/mission	6.5 hr	0.011 lb/sec initial; 0.004 lb/sec final	O ₂ /N ₂	CO ₂ [?]	
MB92/M171 vent	No	Crew	Each MB92 cycle	10 min max	0.125 lb/min	O ₂ /N ₂	CO ₂ [?]	
Scientific airlocks (2)	No	Crew	Each airlock cycle	5 min	0.02 lb/vent	O ₂ /N ₂	CO ₂ [?]	
Scientific bottle vent	No	Programmed	Each R171 cycle	5 min	0.015 lb/vent	O ₂ /N ₂ (0.64 wt%/cycle)	CO ₂ [?]	
Pneumatic bottle vent	No	Programmed	Each R171 cycle	5 min	0.02 lb/min	O ₂ (11.7 lb)	CO ₂ [?]	
Condensate tank bellows vent	No	Crew	Each time condensate tank vented	15 min	0.6 lb/vent	O ₂ /N ₂	CO ₂ [?]	

The Service Module had four clusters of four 100-pound thrust attitude engines each.

These engines were used for orientation before navigation measurements; before Service Propulsion System (SPS) burn for ullage setting; for attitude control during SPS burn; for SM and CM separation; for orbit circularization and matching, and for translation and attitude control during rendezvous and docking.

The Thruster Attitude Control System was a cold nitrogen gas blow-down system with 1372 lb of N₂ available for the Skylab mission. The thrusters were capable of producing a visible plume of condensed and frozen nitrogen particles, but the clearing times of the plumes were quite small. The visible plumes were calculated to dissipate in less than one minute after thruster shutdown, and could momentarily interfere with experiment operation by causing transitory data interference.

The four Stage II retrorocket engines were located on the forward end of the second stage of the Saturn V vehicle.

Each engine provided 35,000 lb of thrust. It was estimated that each engine will expel 188 lb of exhaust material during the 1.5-sec firing time. This produced an average mass flow rate of 125 lb/sec.

Photographs taken during flyaround showed silver-grey deposition on the OWS Solar Array beam fairing, aft skirt, and TACS propellant bottle meteoroid shield. By analyzing the geometry of the observed shadowing, it was determined that the probable cause of the deposition was the S-II retrorockets. However, critical surfaces were shielded and no significant performance degradation was observed.

(5) Extra Vehicular Activity. EVA pressure suit ventilation exhaust particles were a local source of external spacecraft contamination. Most experiment susceptible surfaces were either protected or too remote to be affected. However, three experiments were performed during EVA. Extraneous particles were observed in one experiment's data, but the actual source of the particles is unknown.

b. Experiment/Systems Susceptibility. All Skylab experiments and systems were analyzed to determine their susceptibility to contamination. Critical items were identified from preliminary analyses and in-depth susceptibility analyses were performed on these items.

(1) Experiments Susceptibility. The most significant effects of contamination, either internal to or external to the spacecraft, is the possible degradation of optical experiment results. In addition, contamination could also degrade the data from particle collection experiments and contribute to the degraded performance of systems that are affected by external induced pressures.

The deposition of outgassed species and overboard ventings on optical surfaces is a recognized hazard that can be partially controlled through proper selection and treatment of the materials that are used in spacecraft construction and control of liquid and solid waste disposal. Unfortunately, few measurements have been made of the optical effects of the condensables in the ultraviolet and x-ray regions where available evidence indicates that the effects will be the most severe. Detailed investigations that relate the structure of the contaminant layer to the deterioration of the optical performance of the element are limited.

Contaminant deposits on optical experiment surfaces lead to signal attenuation by means of absorption and/or scattering. Noise can be introduced into optical experiment data by fluorescence, scattering, or wave front distortions. In the case of collection experiments, deposition of contaminants will complicate analysis of the collection surfaces.

An induced atmosphere or cloud of molecules and particles about the spacecraft can also attenuate signal and contribute noise by essentially the same processes. Additionally, the induced atmosphere may raise pressures in high voltage electrical components leading to power losses or corona.

The Corollary, Earth Resources Experiments Package and Apollo Telescope Mount experiments identified as being appreciably susceptible to contamination follow.

- Corollary

- S019 UV Stellar Astronomy
- S183 UV Panorama
- S020 X-Ray Solar Astronomy
- S063 UV Airglow Horizon Photography
- S073 Gegenschein/Zodiacal Light
- S149 Particle Collection
- S150 Galactic X-Ray Mapping
- D024 Thermal Control Coatings
- M415 Thermal Control Coatings
- T025 Coronagraph Contamination Measurements
- T027 Contamination Measurements
- T002 Manual Navigation Sightings

- EREP

- S190A Multispectral Photographic Cameras
- S190B Earth Terrain Camera
- S191 Infrared Spectrometer
- S192 Multispectral Scanner
- S193 Microwave Radiometer Scatterometer/Altimeter
- S194 L-Band Radiometer

- ATM

- S052 White Light Coronagraph
- S054 X-Ray Spectrographic Telescope

S055 XUV Scanning Polychromator Spectroheliometer
S056 X-Ray Telescope
S082A XUV Coronal Spectroheliograph
S082B UV Spectrograph

Experiment susceptibility analyses were performed for each experiment. These analyses included detailed hardware analyses, experiment operational analyses, contamination susceptibility analyses, and recommendations for minimizing the contamination impact. Allowable experiment performance degradation limits were obtained from experiment Principal Investigators and Experiment Managers. These limits were translated into allowable deposition thicknesses, scattering levels, and mass column densities for comparison with contamination predictions.

(2) Systems Susceptibility. The major systems identified as being significantly susceptible to contamination were:

- Thermal Control Surfaces - ATM-STS, OWS, MDA and ATM surfaces;
- Solar Array Systems - ATM-SAS, OWS-SAS;
- Windows - OWS Wardroom Window, STS Viewing Ports, MDA Window, Scientific Airlock Window, GSM Windows;
- Attitude Pointing and Control System - Startracker.

The effect of contamination on these systems was widely varied, but in all cases was expected to be slightly detrimental. Contaminant deposits on thermal control surfaces can result in a change in absorptivity-emmissivity characteristics and cause an undesirable shift in operating temperatures. Contaminant deposits on solar array system surfaces could result in increased radiant energy absorption by the cover slides and panel back surfaces both of which will reduce electrical output. Deposits on windows could reduce transmissivity and increase light scatter resulting in decreased viewing characteristics. Attitude pointing and control system optics could develop imbalances or equipment decreased sensitivity as a result of contaminant deposits. Pollution of the space surrounding the orbiting assembly could result in increased radiation scatter plus spectral absorption; thereby degradation of optical experiment results, especially those concerned with weak radiation sources in the daytime sky.

A methodology was developed for determining the degradation of operational characteristics due to contamination for each of the systems listed. Available test data was used to establish the relative magnitudes of the degradation. This data was later used during prediction, and mission support and evaluation phases.

c. Skylab Contamination Improvement. Based on studies and tests conducted during Skylab contamination control/assessment activities, hardware, and operational changes were implemented to reduce the impact of contamination on susceptible systems. The specific areas affected follow:

(1) Materials. A significant number of material changes were made because of incompatibility between susceptible optical surfaces and material outgassing characteristics.

(2) Vents. Vents were relocated to take advantage of preferred venting directors. Examples include the Mole Sieve and Environmental Control System Condensate Vent. Shielding was installed on some vents including the M512, M479, and PCU to protect sensitive instruments. The primary condensate vent and M092 vent were relocated into the OWS Waste Tank filter system to reduce external particle densities. The contingency condensate vent nozzle was redesigned to reduce the plume dimensions and particle sizes.

(3) Filters. Based on a ground test program, 2.0-micron filters were installed in the OWS Waste Tank to minimize particle fluxes being emitted by the waste tank vents. The filters on the M479, M092, and Habitation Area Vents were modified to reduce particle emission.

(4) Covers. A cover was installed on the OWS aft radiator system to protect it from the S-II retrorocket firing.

(5) Pyrotechnics. All pyrotechnics were of a self-contained design so that combustion products would not contribute to the contamination environment.

3. Interface Requirements. The interface requirements between the contamination "system" and Skylab were established in the form of operational controls and constraints. The controls and constraints were design so that contamination would not compromise the Skylab mission objectives.

The controls and constraints effective between the experiment and vehicle systems were delineated in the Mission Requirements Document. For SL-1/2, they are shown in Table II.K-3. Detailed experiment/vent operational constraints are shown in Table II.K-4.

During the Skylab mission, mission support activities identified certain desired modifications to the controls and constraints developed for SL-1/2 as a result of operational changes and assessment of the contamination environment. Changes to the General Contamination Mission Rules (Table II.K-3) are listed below.

a. Mission Rule 12-5: Delete EREP from contamination alert. Rationale - Cloud brightness levels of 10^{-14} B/B₀, as measured by the T027/S073 Photometer, is well below the EREP sensitivity level.

b. Mission Rule 12-10: This Mission Rule is waived for S054. Rationale - The S054 door was pinned open on SL-2.

c. Mission Rule 12-14: Delete S054 from the Operational Vent/Experiment constraint table. Rationale - The S054 door was pinned open on SL-2.

Table II.K-3. General Contamination Management Rules

<u>RULE NO.</u>	<u>MISSION RULE</u>		
12-2	Deleted		
12-3	CSM RCS firings will be minimized during dock/undock operations.		
12-4	Where possible, experiments will be scheduled so that experiment contamination limits will not be exceeded.		
12-5	If any of the following contamination levels are experienced, a (ATM, EREP, Corollary) contamination alert will be issued by the indicated position:		
	<u>POSITION</u>	<u>SOURCE</u>	<u>INDICATED LEVEL</u> <u>TYPE ALERT</u>
	Corollary	ATM QCM	0.02×10^{-6} gms/cm ² /hr ATM
	Corollary	EREP QCM	0.5×10^{-6} gms/cm ² /hr EREP/Corollary
	ATM	S052	1×10^{-10} B/B0 ATM/Corollary/EREP
	Corollary	T027/S073	1×10^{-14} B/B0 ATM/Corollary/EREP
	Definition:		
	Contamination Alert: A situation where the contamination environment may be sufficiently high to consider changes in the nominal flight plan. An alert will be followed by a conference set up by Corollary which includes the contamination team members, and representatives from the potentially affected discipline.		
12-6	Vents will be planned so that there is minimum impact to experiment operation.		
12-7	Normally during orbit shaping maneuvers, only the CSM +X thrusters will be used.		
12-8	CSM urine and waste water must not be dumped within 1000 ft of the SWS.		
12-9	Deleted		
12-10	Aperture doors and experiment optics covers (including their windows) must be closed except during the data taking periods of the following experiments:		
	<u>COROLLARY</u>	<u>EREP</u>	<u>ATM</u>
	S019	S190A	S052
	S020	S190B	S055A
	T027/S073	S191	
	S063	S192	S082A
	S183	STS Windows	S082B

Table II.K-3 (continued)

<u>COROLLARY</u>	<u>EREP</u>	<u>ATM</u>
T002		H-Alpha 1 H-Alpha 2 Star Tracker S054
12-11	The contingency trash disposal plan will be used in the event of trash airlock malfunction and will be scheduled to have minimum effect in experiment operations.	
12-12	Liquid dumps will be inhibited when Waste Tank pressures > 0.08 psia as indicated by the waste processor outlet pressure or the Waste Tank low pressures. Waste Tank pressures above the triple point of water result in existence of free water in the Waste Tank.	
12-13	Simultaneous liquid dumps into the Waste Tank from more than one source (dump nozzles) normally will not be performed to ensure Waste Tank pressures < 0.08 psia. It may be necessary to inhibit atmosphere dumps into the Waste Tank during liquid dumps from another source.. Trash airlock operation is permissible during liquid dumps into the Waste Tank.	
12-14	Operational vent/experiment constraints matrix (see Table II.K-4).	

The final version of the Operational Vent/Experiment Constraints table is shown in Table II.K-5.

4. Design Verification

a. Contamination Models. As a result of Skylab premission contamination assessment and control activities, three computer programs were developed to provide contamination models for Skylab. These models were developed primarily for premission contamination evaluation and controls, daily mission support, and postmission evaluation. These programs represented a present state-of-the-art understanding of the phenomena of contamination encompassing the physics of the contamination aspect as related to Skylab, summary of all available related ground testing (including specific performance data concerning Skylab vent hardware simulated in large scale ground test programs), and various relationships between contamination and effects on the contaminant sensitive instruments. The three programs used were the Cloud Math Model (CLOUD), Deposition Math Model (ODRAP), and the OWS Waste Tank Model. These models have the following capabilities:

(1) Cloud Math Model: Three dimensional simulation of Skylab geometry;

- Vent characteristics (particle sizes, velocities, plume extent, etc.) and critical experiment lines-of-sight are contained in the model. (Particle sizes, velocities, plume extent, were derived from ground test programs and were adjusted as flight data became available;
- Treats particulate trajectories from various vents;
- Considers residual earth's atmosphere influence (drag) on the particles and the velocity vector of Skylab with respect to the trajectory of particles;
- Considers the effect of sublimation on particles that result from liquid vents;
- Established either the electromagnetic scattering, absorption, or emittance properties of the particles as a function of time.

(2) Deposition Math Model. Three dimensional simulation of Skylab geometry;

- Considers mass source rate as a function of time and temperature for all major outgassing materials and vents;

Table II.K-5. Operational Vent/Experiment Constraints (Final)

VENTS	EXPERIMENTS		COROLLARY												EREP										
	ATM						STAR TRACKER																		
	S052	S054	S055A	S056	H-2 1, 2	S082A	S082B	S020	S063	S149 (IN SAL)	S201	S183	S019	S073	T027/S073	S232	S233	T025	ED 23, 26	S190A, B	S191	S192	S193	S194	
Cabin Atmosphere Vents ²	1					1	1	1 12	6	2	2	2	2 12	2	1	1	1	2		1					1
EVA	1					1	1	1 12	4	11	2	2	2 12	2	1	1	1	2		1					1
CSM RCS	1					1	1	1 12	4	12	2	2	2 12	2	1	1	1	2		1					1
Water Dump (Unbagged) Into Waste Tank										4															
AM Condensate System Vent(Contingency) ⁹	1					1	1	1 12	4	2	2	2	2 12	2	1	1	1	2		1					1
CSM Vents ³	1					1	1	1 12	4	2	2	2	2 12	2	1	1	1	2		1					1
MDA Exp (M512) Vent										4															1
M551, 552, 553								14	4	14	14	14	14	14				14							1
M092								13	4	11	1	1	1	1				11	1						1
M171																									
OVS Exp Vacuum Vent								8	4	8	8	8	8	8	10										8
Condensate Holding Tank Vents(Gas Side)																									

- NOTES:
1. Complete vent 15 min before experiment exposure.
 2. Complete vent 30 min before experiment exposure.
 3. Includes Steam Duct, Urine Dump, Waste Water Dump, and Fuel Cell purges.
 4. Deleted. (Before SL-4 see Note 4 Table II.K-4).
 5. See Rule No. 6-43 for list of vents to be used for atmosphere management.
 6. Deleted. (Before SL-4 see Note 6 Table II.K-4).
 7. Includes Loak Depress Valve and Suit Overboard Vent. Rule waived for S149, T025, S020, or S201 if deployed EVA.
 8. Complete vent 15 min before installation of experiment in anti-solar SAL.
 9. Begin vent after orbital midnight and complete vent before sunrise crossing or double vent constraint times (if not in SI, vent in direction of negative velocity vector).
 10. Complete vent 15 min before installation of experiment in anti-solar SAL. If experiment is already installed, extend 7 rods and place trunnion to zero.
 11. Complete vent 30 min before experiment exposure using Articulated Mirror System (AMS): No time constraint on vent for EVA exposure: Complete vent 15 min before experiment exposure without AMS: Complete vent 15 min before experiment exposure with AMS.
 12. If M092 vents overboard, as in SL-2 and early SL-3, complete vent 15 min before experiment exposure using AMS. No time constraint for M092 vent into waste tank as in late SL-3 and SL-4.

- Considers fraction of this mass capable of impinging on any surface, i.e., considers configuration factors and plume mass distribution;
- Considers temperature of the source of contamination and surfaces impinged upon;
- Considers the fraction of mass capable of condensing on a surface as a function of temperature, i.e., sticking coefficients, and influence of angular considerations to the sticking coefficients;
- Considers resublimation (desorption rate) of the deposited material as a function of temperature;
- Establishes local "pressure" regimes for evaluation of corona susceptible experiments;
- Established degradation in functional properties of specific surfaces as a result of contaminant thickness.

(3) OWS Waste Tank Math Model. Treats quasi-steady state and transient conditions in Waste Tank as a function of vented liquid materials;

- Establishes sublimation rates of liquid materials dumped into the Waste Tank;
- Establishes mass accumulation as a function of time;
- Establishes tank internal pressure as a function of time;
- Establishes gaseous flow rates/mass flow rates through the Waste Tank nonpropulsive vents.

b. Ground Test Programs. Numerous vacuum chamber tests were conducted at various NASA and contractor locations to evaluate specific Skylab waste disposal and venting systems and their influence on Skylab contamination. In many instances, the test results have provided basic data either for an analytical model or qualification of a system with respect to contamination. This section describes the results of three major test programs which provided model data.

(1) Skylab Contamination Ground Test Program (SCGTP). The SCGTP was designed and implemented to accomplish the following objectives:

- Provide quantitative data about the particle size distribution, charge distribution, mass flow characteristics, surface contamination effects, and plume effects during a condensate, molecular sieve, and fecal processor discharge;
- Determine the Orbital Workshop Waste Tank pressure profile, ice accumulation, and constituent behavior during a biocide/urine flush, condensate discharge, soapy water, and urine bag rupture.
- Determine characteristics of the discharge effluent at the two nonpropulsive vents.

All of the above objectives were successfully accomplished. The information obtained was used as basic input data for the contamination models previously described.

(2) Lewis Research Center CSM RCS Engine Plume Definition and Effects. The objectives of this test, using a simulated CSM R4D thruster, were to determine:

- Mass flux distribution as a function of angle throughout the engine plume (including backflow);
- Sticking coefficient and subsequent desorption characteristics of the engine plume material;
- Degradation of thermal control coating and solar cell characteristics as a function of engine plume deposition for simulated Skylab conditions of vacuum environment and Solar UV exposure. The objectives were successfully accomplished and the information obtained was input to the Deposition Math Model.

(3) Ice Particle Sublimation Tests - Dudley Observatory. The objective of this test was to determine the sublimation rates of ice particles subjected to a simulated space environment in order to determine ice particle life times. The objective was successfully accomplished and the data was input to the Cloud Math Model.

(4) Urine Autopressurization Test. The objective of this test was to determine the pressure buildup of urine being stored for a period equivalent to the Skylab mission (9 months) in sealed metal containers. Burst of the urine bags in the Skylab waste tank may have provided a source of contamination from the waste tank vents. The test provided quantitative data under long-term storage that the pressure buildup would not exceed the design limits of the bags.

c. Pre-mission Contamination Predictions. The major considerations in the development of Skylab contamination predictions were mission timeline, source definition, anticipated contamination environment, and variations of source and model parameters. The impingement/deposition of cluster outgassed materials on selected experiments, windows, thermal control surfaces, electrical power system surfaces, and specific contamination monitors was calculated using the Deposition Math Model. Relative susceptibilities of critical surfaces to deposition were determined as a function of cluster position and mission time period. A parametric variation was performed to illustrate how perturbations to major model parameters would affect the predicted contamination levels.

The induced atmosphere mass column densities, light scattering properties, and absorption properties were calculated for outgassing, mole sieve and waste tank venting, and operation of contingency vents using the Cloud and Deposition Math Models. The Waste Tank model provided Waste Tank Vent source characteristics. The predictions were made for sensitive experiment lines-of-sight. The impact of the Environmental Control System Contingency Condensate Vent on the ATM and EREP lines-of-sight was specifically analyzed since the SCGTP results showed it to be a severe source of contamination.

The susceptibilities of experiments, Skylab windows, thermal control surfaces, and electrical power systems were assessed in terms of model predictions of contaminant levels. The degradation of various experiments/systems was assessed against experiment principal investigator/systems evaluator established contamination sensitivity levels.

In addition, predictions were established for those specific contamination detection instruments that were to be used to provide near real-time mission support assessment of contamination and provide validation data for the math models. In light of the predictions, the existing constraints were reviewed for applicability.

The conclusions reached from the results of the prediction analyses was that no experiment/system performance degradation due to contamination was expected if the contamination mission constraints were followed. However, contingency venting of liquids directly overboard would result in high background scattering that would impact experiment performance. Specifically the condensate vent would potentially affect any or all experiment lines-of-sight depending on the cluster orbital position during the venting period.

d. Mission Support/Evaluation. Skylab mission support and evaluation was performed by the Contamination Mission Support Group (CMMSG). The CMMSG performed pre-mission, mission, and post-mission activities. General pre-mission activities included training and simulation, technical discipline team coordination, computer model development, contamination prediction formulation, Data Request Form (DRF)

and Detailed Test Objective (DTO) survey, and launch operations support. Mission support and mission evaluation plans were prepared to define explicitly, the methodology for performance of these activities.

During the mission, the near real-time and periodic real-time data were analyzed to determine trends and establish contamination source information. This trend and source data were used to assess design performance and constraint effectiveness, to update mission predictions, and to resolve anomalies. In addition, the CMSG monitored crew activities and maintained contamination DTO completion status for use in mission planning.

Mission evaluation was the longer term analysis activity, which included assessment of all relative data generated during the mission operation activity period, and also treated postmission splashdown data. This analysis activity evaluated the overall contamination trends, determined the degree of DTO completion, identified anomalies, formulated operational constraint recommendations where required, and provided next mission prognosis.

Specific contamination mission objectives were defined and are categorized into four assessment classifications.

(1) Design Performance Assessment. Design performance assessment was accomplished through evaluation of six areas of interest:

- windows,
- corollary experiments,
- ATM experiments,
- thermal control surfaces,
- solar array,
- star tracker.

Through evaluation of performance levels or condition of these areas during the mission or postmission, the effectiveness of sources control and effects of residual sources was determined. The operation times of controllable vents, window covers, and experiments were used to correlate source emissions versus degradation effects.

(2) Constraint Effectiveness Assessment. The CMSG identified and established operational constraints for operation of certain experiments as system elements during or subsequent to potentially degrading controllable vents. Generally, these constraints were developed to minimize exposure of sensitive elements to the sources through application of estimated source cleaning times. During the mission, it was necessary to evaluate the effectiveness of these constraints, identify constraint violations, and determine impact, and recommend operational changes if conditions were worse than originally predicted.

(3) Prediction Assessment. Data from Skylab were analyzed to determine source impact on sensitive experiment and system

surfaces. These impacts were compared to initial (prelaunch) predictions and models were adjusted to account for any discrepancies. The refined models were then used to predict conditions for subsequent missions, and refine, eliminate, or develop operational constraints as necessary.

Based on computer math modeling of the contaminant environment around Skylab, contamination prediction summary reports were generated on a daily basis during SL-1/2 and weekly for the remainder of the mission. The reports contained contamination deposition predictions for critical operational surfaces and experiments along with the induced environment predictions of mass column densities and radiant scattering. Table II.K-6 is the final prediction summary for the Skylab Mission. These summaries were used by JSC for mission planning and assessment.

(4) DTO Assessment. The CMSG identified DTO functional objectives (FOs) that were implemented to obtain data to support contamination assessment and evaluation. In general, the data developed from the FOs involved the use of crew time in visual observations and photographic sequences. Because of the manual nature of the data acquisition, the CMSG monitored the on-going manned activities versus planned activities, and kept a running assessment of completion for each FO. Off-normal conditions and/or missed events resulted in recommendations for downstream events or alternate operations. The FOs performed during the Skylab mission and their objectives were as follows:

- Obtain data on the contamination effects of certain OA vent plumes and how these vent plumes and associated contamination change with the durations of the mission.
- FO-1) Observe, photograph and comment on the characteristics of certain OWS vent plumes early in the mission.
- FO-2) Observe and comment on certain OWS vent plumes during mid-mission.
- FO-3) Observe, photograph, and comment on the characteristics of certain OWS vent plumes late in the mission.
- FO-4) Observe, photograph, and comment on the characteristics of certain OA vent plumes as they occur during the mission.
- Obtain data concerning the contamination on certain OA windows and how this contamination changes with the duration of the mission.
- FO-5) Observe, photograph, and comment on the characteristics of window contaminants early in the mission.

Table II.K-6. Contamination Prediction Summary

EXPERIMENTS	EXPERIMENT SENSITIVITY ①			PREDICTIONS ②		
<u>CLOUD</u> Cloud (B/B ₀) Column Density Deposition (Å)	Not Available			7.6 x 10 ⁻¹⁵ (157) 1.4 x 10 ⁻¹⁴ (157) ③ 0.0 (039)		
<u>COROLLARY:</u> <u>CLOUD (B/B)</u>						
S190A	3.7 x 10 ⁻⁹	④		5.03 x 10 ⁻¹⁷	(364)	
S190B	3.7 x 10 ⁻⁹	④		1.6 x 10 ⁻¹⁶	(364)	
S191	4.0 x 10 ⁻⁹	⑤		5.03 x 10 ⁻¹⁷	(364)	
S192	4.4 x 10 ⁻⁹	⑤		5.03 x 10 ⁻¹⁷	(364)	
S193	Not Applicable	⑤		Not Applicable		
S194	Not Applicable	④		Not Applicable		
S063	3.3 x 10 ⁻¹⁰	⑥		2.7 x 10 ⁻¹⁶	(031)	
S019	Not Applicable	⑤		Not Applicable		
S183	Not Applicable	⑤		Not Applicable		
S073	1.0 x 10 ⁻¹³	⑥		1.0 x 10 ⁻¹⁶	(216)	⑦
S201	Not Applicable	⑤		2.7 x 10 ⁻¹⁶	(033)	
T025/S073	1.0 x 10 ⁻¹³	⑥		5.9 x 10 ⁻¹⁶	(355)	
S063K	3.3 x 10 ⁻¹⁰	⑥		4.6 x 10 ⁻¹⁵	(348)	
S019K	Not Available			7.2 x 10 ⁻¹⁵	(340)	
S183K	Not Available			7.5 x 10 ⁻¹⁵	(341)	
S201K	Not Applicable	⑤		7.0 x 10 ⁻¹⁵	(339)	
S020K	1.2 x 10 ⁻⁸	⑥		4.6 x 10 ⁻¹⁵	(363)	
S233	Not Available			7.5 x 10 ⁻¹⁵	(341)	
T025K	1.0 x 10 ⁻⁹	⑥		4.6 x 10 ⁻¹⁵	(363)	
<u>COROLLARY:</u> <u>DEPOSITION</u>	Å	% ⑧	µg/cm ²	Å	% ⑧	µg/cm ²
S190A	50	0.5	0.5 ④	0	0	0 (032)
S190B	50	0.5	0.5 ④	0 ⑨	0	0 (032)
S191	300	3.0	3.0 ④	0	0	0 (032)
S192	560	5.0	5.6 ④	0	0	0 (032)
S193	2.5x10 ⁶	0.5	2.5x10 ⁴ ④	231.6	<1.0	2.316 (032)
S194	2000	20	20 ④	0	0	0 (032)
S063AMS SL-3	240	50	2.4 ④	2.6	1.0	0.026 (233)
S063AMS SL-4	240	50	2.4 ④	1.5	<1.0	0.015 (029)
S063 ASAL	960	50	9.6 ④	0	0	0 (023)
S063 (STS)	960	50	9.6 ④	94	5.8	0.94 (031)
S063 (WRW)	960	50	9.6 ④	175	10.5	1.75 (031)
S019 SL-3	11	10	0.11 ④	2.6	2.7	0.026 (233)
S019 SL-4	11	10	0.11 ④	1.6	1.6	0.016 (025)
S183 SL-3	18	10	0.18 ④	1.5	1.0	0.026 (233)
S183 SL-4	18	10	0.18 ④	1.6	<1.0	0.016 (029)
S073	N/A	N/A	N/A ⑤	0	N/A	0 (216)
S201	N/A	N/A	N/A ⑤	1.6	N/A	0.016 (033)
T025/S073	N/A	N/A	N/A ⑤	0	N/A	0 (023)

N/A: Not Applicable

Table II.K-6. (continued)

EXPERIMENTS	EXPERIMENT SENSITIVITY			PREDICTIONS		
COROLLARY: DEPOSITION	Å	% 8	µg/cm ²	Å	% 8	µg/cm ²
T025/S073 w/AMS	N/A	N/A	N/A (5)	1.6	N/A	0.016 (030)
S063K	200	50	2.4 (4)	1.5	<1.0	0.015 (029)
S019K	11	10	0.11 (4)	1.5	1.4	0.015 (030)
S183K	18	10	0.18 (4)	1.0	<1.0	0.010 (011)
S201K (EVA)	N/A	N/A	N/A (5)	4.0	N/A	0.040 (363)
S201K (AMS)	N/A	N/A	N/A (5)	1.6	N/A	0.016 (032)
S020K (EVA)	200	1.0	2.0 (6)	4.0	0	0.040 (363)
S233 (CSM)	Not Available			5850	10	58.5 (345)
S233 (STS)	Not Available			94.7	<1.0	0.947 (032)
T025K	N/A	N/A	N/A (5)	5.1	N/A	0.051 (363)
SYSTEMS				PREDICTIONS DOY 039		
SOLAR ARRAY SYSTEM ACCUMULATIVE POWER LOSS (%)						
OWS SOLAR ARRAY GROUP (1-4)				3.43 %		
OWS SOLAR ARRAY GROUP (5-8)				2.92 %		
ATM SOLAR ARRAY SYSTEM				0.00 %		
THERMAL CONTROL SURFACE ACCUMULATIVE Δα						
ALL SURFACES:				+0.190%		
CONTAMINATION DETECTION INSTRUMENTS ACCUMULATIVE (g/cm ²)						
EREPA X QCM (CSM FACING)				52.08 x 10 ⁻⁶		
EREPA -X QCM (OWS FACING)				60.77 x 10 ⁻⁶		
EREPA -Z QCM (ANTI-SOLAR) -2				0.0 (9)		
ATM QCM (DAILY RATE) -2				0.0		
T027 X QCM				N/A		
T027 Z QCM				N/A		
WINDOWS - ACCUMULATIVE TRANSMISSION LOSS						
STS:	DEPOSITION (g/cm ²)			9.549 x 10 ⁻⁷		
	TRANSMISSION LOSS (%) @ 6000Å			0.095 %		
	@ 3000Å			3.15 %		
WARDROOM:	DEPOSITION (g/cm ²)			1.78 x 10 ⁻⁶		
	TRANSMISSION LOSS (%) @ 6000Å			0.155 %		
	@ 3000Å			5.8 %		
CSM:	DEPOSITION (g/cm ²)			SL-2:	1.38 x 10 ⁻⁴	
				SL-3:	2.31 x 10 ⁻⁴	
				SL-4:	1.50 x 10 ⁻⁴	
	BRIGHTNESS LOSS (%) (10)			SL-2:	21	
				SL-3:	31.5	
				SL-4:	23	

SEE NOTES ON FOLLOWING PAGE

Table II.K-6 (continued)

NOTES:

1. Sensitivities are based upon the most susceptible wavelength of a particular experiment.
2. Predicted deposition levels are based upon accumulative deposition over operational time frames of systems or experiments. B/B_0 predictions presented are for the highest levels witnessed during the Skylab mission. Day-of-Year (DOY) that these levels were reached are indicated in parenthesis beside each prediction.
3. Column density predictions are based on total molecular column density in g/cm^2 .
4. Sensitivity based on tolerable percent degradation quoted from experiment P.I. and ensuring calculation of tolerable B/B_0 and deposition levels.
5. Sensitivity quoted directly from experiment P.I.
6. Sensitivity calculated from known experiment characteristics and objectives.
7. Preliminary flight data indicates B/B_0 readings in the 10^{-14} range.
8. Signal loss percent.
9. Flight data from the -Z facing Quartz Crystal Microbalance-Contamination Sensor (QCMs) indicates a deposition rate of approximately $12\text{\AA}/\text{day}$. The only source appears to be localized outgassing from the X facing QCM connectors, which are in the field-of-view of the -Z QCMs. This is believed to be a localized condition and not representative of Skylab outgassing, although the effect of ambient reflection has not been totally assessed at this time. Therefore, math modeling continues to use zero deposition on the -Z QCMs and the -Z facing EREP experiments including S191, which had its outer door left open for 40 days during SL-3.
10. CSM window brightness loss is the visible transmission loss based on the spectral response of the human eye.

- F0-6) Observe, and comment on the characteristics of window contaminants during mid-mission.
- F0-7) Observe, photograph and comment on the characteristics of window contaminants late in the mission.
- F0-8) Observe and comment on the characteristics of window contaminants during normal viewing times.
 - Obtain data concerning contaminants on experiment optical surfaces as the experiments are used during the mission.
- F0-9) Observe and comment on the characteristics of the contaminants on experiment optical surfaces as the experiments are used during the mission.
 - Obtain data concerning OWS vent plumes and contaminants deposited on certain OA external surfaces as viewed during EVA.
- F0-10) Observe and comment on OWS vent plumes and contaminants on external surfaces during EVA.

5. Conclusions and Recommendations. At the conclusion of the Skylab mission, the mission evaluation indicated that the methodology and modeling techniques developed were valid, and that the contamination control measures instigated during the design, development, and operational phases of this program were adequate to reduce the external contamination environment, in many instances, to below the threshold sensitivity levels for experiments and affected subsystems.

The following specific conclusions were reached as a result of Skylab contamination control/assessment activities.

a. Contamination Control Working Group. A CCWG is a vehicle for integrating contamination design requirements, determining systems interactions and contamination effects on all systems as well as managing technical contamination studies. Future programs should consider contamination control as part of system integration efforts.

Under the guidance of the CCWG extensive testing of Skylab systems including the Waste Management System was performed to predict contamination levels. Design changes and operational procedure changes were recommended by the CCWG to limit contamination. Rigorous analyses were performed in conjunction with testing to model performance of the contamination producing systems and to predict contamination levels. Flight experience confirms that this multidiscipline approach is successful and required for complex space vehicles.

b. Surface deposition contamination and induced cloud brightness levels can be predicted within ± 30 percent. Total contamination of the vehicle can be predicted fairly accurately if periodic updates of mission critical parameters and as-flown conditions are made.

Adequate premission predictions of surface deposition and induced cloud brightness around the Skylab vehicle were made. In order to keep the model results up-to-date, periodic revisions of the contamination parameters were required and found desirable as the actual mission deviated from nominal. The contamination model was updated because mission changes, anomalies, and contingencies had a major impact on the contaminant environment.

The line-of-sight model for surface deposition contamination was shown to predict contamination levels within 10 to 20 percent. Modeling of the induced cloud brightness around the Skylab was found to be dependent on parameters identified during the Skylab Contamination Ground Test Program and were mission dependent.

c. The use of instrumentation to measure contamination deposition and cloud brightness are invaluable in assessing and predicting experiment degradation, contamination levels on critical surfaces and as reference points for updating contamination prediction models. Mass deposition monitors, low pressure sensors, residual gas analyzers and cloud brightness monitors are recommended for these purposes.

Quartz Crystal Microbalances were successfully used on the exterior of the Skylab vehicle to monitor mass deposition rates at specific vehicle locations and cloud brightness monitors were used to detect the brightness of the induced atmosphere around the vehicle. The accuracy of the prediction model was improved by using these measurements as specific reference points.

d. Testing and flight observations have shown that discharging waste water into a waste tank that is exposed to vacuum, is successful in allowing only vapor to escape, thus protecting against particle production from major waste liquid sources. The mode of waste liquid ejection is recommended for long term missions on those requiring elimination of large quantities of waste liquid where storage is not feasible.

The waste tank concept of eliminating liquid waste has been instrumental in reducing the brightness of the induced atmosphere around Skylab. The system has been operating within the guidelines established for normal operation during ground testing.

The following recommendations apply to future manned space program contamination control/assessment activities.

a. Contamination control considerations should be integrated into the initial spacecraft design concepts and should be a prime factor in mission design and planning.

As a result of the Skylab program, it is evident that contamination control should be integrated into the design criteria on a level comparable to thermal and power systems and should be considered from the initial stage, through mission support. It is recommended for future missions that a contamination control system integrate the degradation effects resulting from interactions that occur between all contributory systems.

Systems affected by contamination on Skylab were thermal, power, attitude pointing control, environmental control, crew safety, and all experiments or critical and operational surfaces such as windows and antennas. Proper timing of experiments and scheduled venting activity can reduce the levels or the potential of contamination.

b. A uniform materials testing criteria should be established to determine those parameters required for accurate modeling and assessment.

Success of contamination modeling and subsequent counter-measures is dependent upon extensive materials testing for source rates over the range of temperatures, times of exposure and ambient environment interactions anticipated. Resultant deposition capability must be determined for major sources as a function of temperature variations of source and sink, and the contaminant effects on signal attenuation.

Source rates for major outgassing sources on Skylab were inferred from preliminary in-flight measurements and were nearly a constant rate for a given temperature profile after months of exposure.

c. To reduce the contamination of overboard venting of liquids and gases, adequate testing, design and analysis is required.

The Skylab Contamination Ground Test Program demonstrated the need for testing of vent systems to determine parameters required, and evaluate vent nozzle designs. Overboard vents did not deposit on Skylab exterior surfaces because of the relatively warm temperatures. Experience has indicated that particle size distribution, direction, and velocity can be created by proper nozzle design and flow rates for a given liquid that can take advantage of sublimation characteristics and ambient atmosphere drag effect to minimize contamination levels. Given these parameters, modeling can determine proper timelines and vent sequences. Alternative methods to venting overboard for sources unacceptable in a vent mode should be established.

d. Proper timelines for experiment exposure or operation in relation to engine firings, outgassing levels, and overboard venting are necessary to ensure low contamination levels.

The two types of contamination will be surface deposition or a total mass column density along a particular line-of-sight. For different altitudes, the clearing time of particles and molecular interactions with the ambient atmosphere should be considered.

By modeling vents and engine firings, the periods where an experiment or critical surface should be protected can be determined. This approach for Skylab has been successful. Particles have been observed by experiments when the predicted clearing time of particles were not adhered to.

e. Future spacecraft with cryogenic surfaces will be highly susceptible to all vents and leaks, even from non line-of-sight impingement, resulting from ambient atmosphere interactions and sublimation processes.

Of all the sources of contamination on a manned vehicle, outgassing and engine firings are a major problem because of the continuous, long lasting nature of outgassing, and the necessity of engine firings for rendezvous, docking, and attitude control. Other major venting can be adequately designed, controlled, or timed to minimize cloud brightness or deposition potential.

Observations of mass deposition rates on mass detectors on the exterior of the Skylab vehicle indicated that outgassing sources and engine firings were the major contributors to deposition. Other vented or leaked material did not deposit at the temperatures of the Skylab exterior.

f. The contamination control of all experiment and vehicle components should have a uniform set of specifications that encompasses the susceptibility of the most critical surfaces. Documentation and monitoring by a single organization should exist from production to launch so that a central record is maintained for the entire vehicle. Because of greater experiment sensitivities on future missions and multiple interfaces anticipated, a higher degree of ground control is considered necessary.

In general, it can be stated that prelaunch cleanliness was well controlled and, aside from minor problems, no adverse effects can be attributed to prelaunch contamination.

g. The capability to clean accessible optics or the development of techniques to clean remote optics is highly desirable. New techniques for contaminant detection and cleaning exist and should be thoroughly investigated for future application. These include Auger spectroscopy, binary scattering, metastable beams, ion sputtering and activated plasmas. Vacuum or GN₂ stowage for sensitive optics should be used.

Onboard Skylab optical cleaning kits for accessible optics consisted of a mild detergent solution, distilled water, lint-free cotton, brush, lens tissues, and convoluted bellows, and have been successful in removing contamination from certain Skylab surfaces. However, these techniques will not remove many contaminants such as deposited outgassants from external sources. Stowage techniques appear to have been satisfactory.

L. Crew Systems

1. Design Requirements. The Skylab DWS concept was firmly established in the summer of 1969. Concurrent with the decision was the initiation of a concerted effort to firmly define the man/machine interfaces. Specific Crew Systems documentation existing at the time that was mandatory for the total cluster included:

- MSFC RS003M00003
"Cluster Requirements Specification" dated August 1969
(specifically appendix G, titled "Crew Systems Design
Integration Requirements)."
- MSFC 10M32447A
"Human Engineering Design Requirements for AAP Experiments"
dated February 1969.
- MSFC 10M32158A
"Man/System Design Requirements for Orbital Workshop, Multiple
Docking Adapter, Airlock Module, and Apollo Telescope
Mount" dated March 1969.

Each of the documents was a working document and was subject to revision during the design and build phase of the Skylab program.

In addition to the preceding listed documents, there were two human engineering criteria documents. The documents were:

- MSFC-STD-267A
"Human Engineering Design Criteria" dated September 1966.
- MIL-STD-1472 (DOD)
"Human Engineering Design Criteria for Military Systems,
Equipment, and Facilities" dated February 1968.

The remaining documented crew systems design requirements were the individual module Contract End Item Specification. These documents contained a functional and performance description of each identified item to be delivered.

In addition to the contractual documentation, specific requirements evolved and were recognized as a result of active participation by flight crewmembers in reviewing and monitoring the design progress. Frequent formal crew reviews were held at NASA Centers and contractors facilities and included at least one prime crewmember. The accumulative inputs from the crew increased the "workability" of the Skylab, saved time in task performance and, most importantly, gave the astronauts the interior arrangement and man/machine interfaces they desired.

2. Functional Description. When the decision was made to launch the DWS, the pantry concept of the MDA changed to hardmounting most of the previously stowed experiments. This allowed both ATM and EREP to be launched in place with the control panels in the MDA. Situated aft of the MDA, the AM/STS was originally designed to provide EVA capability. The STS module provided the cluster with its two gas control systems, power distribution system and controls, and the data and communications systems. When the ATM C&D panel was added to the MDA, the STS crew station had to accommodate crew functions, for ATM and STS.

At the onset, activities associated with the OWS consisted of little more than demonstrating that a spent propulsive stage could be rendered safe enough for crew entry. The number of separate compartments was held to a minimum --- a large forward compartment, an aft experiment area (primarily devoted to biomedical experimentation) a combined waste management and hygiene compartment, a food management compartment, and sleep compartments. The open grid, which was widely used in the OWS for floors, ceilings, and partitions, served two important functions; it allowed free flow of ventilation air, and it provided crew mobility and stability aids.

The DWS concept permitted more ambitious mission planning and improved habitability i.e., an active food freezer/chiller system was added to improve the quality of food. Additionally, because the OWS would never be exposed to liquid hydrogen, it was possible to add an observation window, relocate the scientific airlocks from the STS to OWS forward area and place an airlock across the LOX/LH₂ common bulkhead to create a trash bin in the otherwise unused oxidizer tank. All the items previously to be launched stowed in the MDA for later deployment in the OWS were launched in place, which greatly reduced activation time.

During the early evolution of the OWS, designers consciously attempted to retain a visual gravity vector, that is, one surface was designated the floor and all nomenclature and operations were planned around this reference surface. Although it was recognized that up and down designators are arbitrary in a weightless environment, it was felt that unless there was strong reason to deviate from the chosen convention, it should be observed. As design evolved, certain deviations were made in the OA. In the OWS, sleep restraints were suspended between the floor and ceiling, and use of the waste management compartment demanded that the crewmen sit on the wall. Moreover, in other parts of the vehicle design considerations appeared to legislate against maintaining consistent layout conventions. In the MDA, operation of the ATM C&D and Experiment M512 required a crew position approximately 90 degrees to the vehicle center line, and monitoring of the nearby STS and EREP controls and displays required that crewmen orient themselves parallel with the vehicle axis.

The following paragraphs of this Section discuss the various means of design verification, simulation, and test programs of the crew systems aspects of Skylab. Mission results and evaluation of Skylab Crew Systems performance are covered in MSFC TMX-64825, MSFC Skylab Crew Systems Mission Evaluation Report, July 1974.

3. Design Verification. Analysis and verification of Skylab Crew Systems Design was accomplished through a series of task analyses, procedural walkthroughs, and informal and formal incremental design reviews. The task analyses, conducted by the individual module contractors, evaluated the operational aspects of each module crew station or crew function and served to establish basic hardware requirements. During this phase of analysis the design was in its early preliminary stages with no mockup hardware available for crewmen to evaluate.

The second phase of analysis and verification was to evaluate the man/machine interface using contractor task analyses in conjunction with early mockups. The mockup studies were used to evaluate the functional aspects of each hardware item as it developed into a firm design. Both task analyses and mockup reviews were used extensively in verifying the conceptual and preliminary design phases of hardware development. The verification was accomplished through informal and formal incremental design reviews.

Incremental design reviews that involved MSFC, contractors, and flight crews were held from the preliminary phases of the design through flight hardware development. The earliest reviews were informal and at a system or subsystem level. Actual crew system design evaluation and verification at the module level occurred as PDRs when an entire module evolved from conceptual to preliminary hardware design stage. As new systems were developed, incremental informal reviews were held. The incremental reviews continued through the entire Skylab hardware design up to final hardware acceptance at KSC before launch.

Following the PDRs were the formal Crew Station Reviews (CSRs) and CDRs. The CSRs constituted the final flight crew approval of preliminary designs before CDRs. Subsequent to the CDRs, additions or changes to the hardware design were evaluated through informal incremental reviews and required CCB approval before implementation.

The Crew Compartment Stowage Reviews (CCSRs) were the final verification before flight hardware integrated testing. Flight Crew Equipment (FCE) including all stowage items, was fit checked to its corresponding interface location. These FCE to interface locations included all stowage containers/locations and use locations.

The following paragraphs will discuss the analyses and reviews for all Skylab modules and systems.

a. Task Analyses. The task analyses contained descriptions of on-orbit crew tasks involving Skylab hardware. Task descriptions included background information, task time, number of crewmen required, procedural description, location of task, interior ambient conditions during task, estimated energy required to perform each task element, hardware used to accomplish task, documents used in the analyses and significant remarks concerning the task. The task analysis format was developed by MSFC to describe crew tasks at the most basic level from which more specific descriptions could be generated. A separate analysis was presented for each crew function. The analyses were an ongoing effort throughout the development phase of Skylab hardware.

The task analyses were used initially as a basis for Skylab hardware design, i.e., to define functional requirements to initiate design solutions and subsequently to resolve discrepancies between the hardware and its use by the crew. Still later in the program they were used as inputs to mission timelines, maintenance, contingency procedures, and finally as inputs for training and flight procedures.

b. Preliminary Design Reviews. As design advanced from conceptual to preliminary hardware designs, incremental and total systems/module design reviews were conducted. At these reviews each hardware contractor presented preliminary designs, supporting documentary analyses, studies, etc., to the MSFC, JSC, and Headquarters review teams. The teams usually consisted of three or four MSFC representatives and one flight crew representative to review an experiment or subsystem with a single contractor engineer. These informal incremental reviews were conducted on all Skylab hardware from program definition to launch, with emphasis in the latter stages shifting from preliminary design to significant design change.

Formal system or module level PDRs were conducted as the program evolved complete systems or modular designs. The first formal PDR to be held was on the OWS in May 1967. From its first formal PDR, subsequent OWS design reviews were conducted as informal incremental reviews. Informal incremental design reviews were also conducted on the AM, MDA, and ATM to monitor their design evolution. The last system PDR to be conducted was for the EREP in May 1970.

On December 2, 1969, a Skylab Cluster System Design Review (CSDR) was conducted at MSFC as a PDR of all Skylab subsystems/systems and modules as an integrated spacecraft. Any discrepancies the flight crew found on any of the Skylab hardware design during the PDR stage were generally rectified by simple design changes with minimal hardware schedule impact. In instances where the solution to a crew discrepancy involved a major system or design change, program impact assessment was performed to determine the necessary course of action. This type of activity was held to a minimum because most problems were identified and solved through the incremental crew reviews held before the CSDR.

c. Crew Station Reviews. Crew Station Reviews used flight or flight-type hardware (high fidelity mockups or one-g trainers) in performing crew reviews of system/module level crew stations and crew working environments. The reviews were conducted to procedures generated directly from task analyses performed during the preliminary design. The objectives of the CSRs were to verify an acceptable crew station environment from the standpoint of accessibility, ease and effectiveness of functional operations, adequate light, low noise levels, adequate identification and understandability of all crew interfaces, and crew safety. Discrepancies at this point were considered as program changes and required RID action. Working groups composed of NASA Program and Technical Representatives reviewed the RIDs to determine corrective action to be taken. Decisions were based on a tradeoff between desirability of RID objectives and resulting program impact.

Initial CSRs were held on the OWS in May 1967 and February 1968, with the final CSR conducted in September 1970. A combined AM/MDA CSR was conducted in July 1970. The initial ATM CSR was held in August 1969, with the final conducted in August 1970. The review included both IVA and EVA crew station tasks. Following the formal CSRs, progressive or incremental CSRs were conducted to assure that disposition of RIDs from the CSRs was accomplished.

d. Critical Design Reviews. The final crew systems verification of hardware design was performed during the CDR phase. Each CDR baselined the module/subsystem design and subsequent changes required CCB action. The effective use of incremental crew reviews as an ongoing effort minimized the impact of crew changes on baselined hardware.

The final formal design review before integrated test and checkout was the Skylab CSDR conducted on July 8, 1971. Any resulting crew interface discrepancies identified during the CDR/CSDR phase were incorporated if shown to have minimum program impact, negotiated as crew-mandatory changes resulting in moderate program impact, or left open to be investigated during the functional integrated testing after flight hardware delivery. Any crew systems changes after CSDR required program direction to modify flight hardware and were subsequently verified during Skylab systems tests, such as Crew Compartment Fit and Function (C²F²).

Following CDR, the SOCAR were conducted incrementally from January 1972 through June 1972. Crew system participation was included in the Special Emphasis, EVA Systems, and Microbial Control review teams. The special emphasis review team assessed the waste management, water, illumination, food management, activation/deactivation, inflight maintenance, and trash management systems and activities. The EVA systems review team assessed the pre-, during and post-EVA activities as well as EVA system hardware including flight crew equipment. The microbial control review team assessed the potential internal contamination and the housekeeping, food handling, and personal hygiene tasks to be performed.

In the EVA area the SOCAR was extended to cover the period up to launch by transferring unresolved action items to the EVA operations planning committee (EVA Ops) with joint MSFC, JSC, and contractor representation. Monthly meetings by the committee were extremely valuable to the EVA discipline in maintaining liaison between all agencies involved, in quickly resolving questions as they arose, and in coordinating final stages of premission activity (training, C²F², contingency analyses, etc.). The EVA Ops team was then able to perform real-time mission planning and problem solving after launch. The effort included almost all the support for planning and conducting the EVA contingency activities during the mission.

e. Crew Compartment Stowage Review. The final stage in flight crew verification of the Skylab hardware design was the CCSR. Using flight hardware/high fidelity mockups and one-g trainers, the flight crew performed fit check, stowage, and inflight use location interface verification checks. During these reviews all Skylab FCE was fit-checked with, or interfaced with, its stowage and use locations. Also verified during

these reviews were FCE accessibility, ease of installation, removal and stowage, proper identification and nomenclature and, finally, its ultimate safety when used by the crew in flight. Discrepancies arising as a result of CCSRs were treated in the same fashion as RIDs resulting from the CSRs and CDRs. Due to potential program impact every effort was made to minimize RIDs at CCSRs by informal incremental crew reviews during the final definition phase. The CCSRs were conducted on the OWS in April 1971 and the combined AM/MDA in September 1971.

4. Simulations. Three types of mockups were used to verify the adequacy of hardware design. These included mockups to demonstrate one-g, zero-g and Neutral Buoyance (NB) methods of simulation. The man/system simulations requirements defined the simulation method and mockup fidelity for each task. In addition to prelaunch hardware/procedure evaluation, all simulation methods were used in EVA systems development and training. A detailed presentation of the EVA procedures, training, hardware, and facilities development program is contained in MSFC TMX-64825-MSFC Skylab Crew Systems Mission Evaluation Report, dated July 1974.

a. One-g Mockups. The one-g mockups for Skylab began as cardboard and plywood gross envelopes. This type of mockup was used to check dimensions and arrangements of Skylab equipment. The next phase was to develop engineering mockups and they ranged in fidelity from basic envelope to flight configuration and were used to verify structural design and crew interface. On completion of the design phase of Skylab, many of these engineering mockups were refurbished and used as one-g trainers. Examples of these uses were: MDA, AM, STS, ATM, and SWS trainers. One-g mockups were also used for special applications and examples are wire bundles, the CM tunnel section, and the SWS hatch section. The final stage of the one-g mockup development was mission support mockups. Static test articles of the ATM, MDA, AM, STS, and SWS were refurbished and used for mission evaluation. Examples of this type were solar array deployment, thermal shield operation, rate gyro installation, and addition of coolant to the heat exchanger. One-g mockups were used by design engineers for evaluation of design and by astronauts for verification of crew interface. From the crew viewpoint the fidelity of one-g mockups was extremely important. When the crew was called on to critique a unit of hardware at a review, i.e., PDR, CDR, the earlier a high fidelity mockup was available the easier it was to achieve a satisfactory crew interface. A good example of this principle was the multipurpose electric furnace for experiment M518. The experiment was introduced late in the program, which made the timeline critical. At the PDR a high fidelity mockup was present and the crew worked the usual problems, nomenclature, location of gages and switches on the C&D panel, and hardware operation. At CDR the crew reviewed the changes and accepted the hardware with few comments. This was in contrast to other units where no high fidelity mockups were available until CDR, and the crew changes requested had an impact on cost and schedule, which could have been avoided by earlier introduction of high fidelity mockups.

Special task mockups were employed by Skylab in the medical experiments area. The Skylab Medical Experiments Altitude Test (SMEAT) was a major example of this type of one-g simulation. The SMEAT mockup was a

vacuum chamber configured to resemble part of the OWS crew quarters and medical experiments area. The simulation conducted was a 56-day mission with three members of the astronaut corps serving as subjects. The facility duplicated the Skylab atmosphere, crew activities, timeline of events, and mission support. The objectives of the simulation were to evaluate the following areas: crew procedures, flight hardware, data handling and reduction, medical support, and baseline medical data acquisition. Results of the simulation were useful for changes in medical experiment hardware, crew diet, crew procedures and medical data handling. Loss of weight in one crewman and significant individual crewman preference in food resulted in diet changes, and an ergometer breakdown, urine volume measuring problems, and blood pressure measuring problems resulted in hardware redesign.

b. Neutral Buoyancy Mockups. NB mockups began as gross envelopes of work areas. A mockup of this type was the SWS. The unit was a shell and was used mostly to represent volume in the cluster. Some of the NB mockups of this type were modified during the Skylab development phase. The MDA, which was outfitted with experiment envelopes, crew restraint devices, and film vaults, is an example. The MDA was used for early evaluation of crew stations. Another type of NB mockup was a combination of a development article and a trainer. This type of mockup was the AM-ATM complex. The unit was used for developing crew equipment and procedures in EVA and contingency EVA, boom transfer operations, boom replacement, clothesline transfer of ATM equipment, film tree locations, and work station evaluation. The unit was used for all EVA training. Part task NB mockups were used for crew evaluations in some experiment areas, i.e., the Lower Body Negative Pressure Experiment.

The MSFC Neutral Buoyancy Simulator (NBS) provided a simulated zero-g environment in which astronauts and engineers performed for extended periods of time, the various phases of spacecraft operations in order to gain first-hand knowledge of hardware and total system operational characteristics. Before SL-1 launch the NBS was used primarily for EVA systems and procedures development, EVA crew training, and mission timeline development. After the SL-1 lost its meteoroid shield, the NBS was used extensively to evaluate potential flight fixes via EVA. The contingency procedures thus developed aided in a successful fix that permitted Skylab to exceed the originally planned mission.

c. Zero-g Aircraft Mockups. The zero-g aircraft mockups were part task mockups used to evaluate design and verify crew interface. Selected activities for each module in the cluster were performed. Command module activities included rescue, with five pressure suited subjects involved, and data transfer. The MDA activities included fireman pole translations, ATM restraint, ATM-STS work envelopes, film vault and film tree operations, MDA pressure suited entry, M512 restraint platform and work envelope, M512 metals melting and sphere forming, fan replacement, and evaluation of various electrical connectors. AM activities included ECS canister changeout, hatch operations, light replacement, umbilical management, water gas separator replacement verification, AM pressure suited working volume that included the ATM film tree, canister operations, and clothesline transfer. SWS activities included the tape

recorder, food consistency, water squeezer operations, OWS stowage lockers, M508 task board, fecal collector, SAL with Experiments T025 and T027, M171 ergometer, M131 rotating litter chair, sleep restraints, and fire extinguishers. Skylab-related research and development activities included pushoff and impact tests, large mass transfers, camera operations, electric shaver evaluation, whole body shower, tool kit, and mechanical restraint. Zero-g aircraft simulations were evaluated by contractor personnel, NASA engineers and astronauts. Results of these simulations were distributed to design engineers. The zero-g tests resulted in both design changes and verification of current design. Zero-g aircraft development mockups were used in areas where zero-g dynamics (mass, fluid, gas) were important.

5. Testing. Operations most important to crew systems were the stowage operations and C²F². The C²F² consisted of a crewmember(s) replacing an installed flight unit with a stowage or replacement item. The system was then functioned to verify its operability. The objective of the test was to verify that inflight maintenance tasks could be performed and that designated spare units would function when connected to the systems.

Fit checks of all hardware were accomplished during the tests to verify that the items would fit in use locations. The fit checks were signed off on a fit check matrix. All flight hardware that was not available in St. Louis, Huntington Beach, Denver, and Huntsville received fit checks at KSC. These were performed by astronauts or their designated representatives.

Stowage operations involved development of test procedures to stow the vehicle for launch and to supply the correct vehicle configuration for the many other tests throughout the Skylab test program.

a. Orbital Workshop. Postmanufacturing checkout of the OWS was accomplished at MDAC-WD in the Vehicle Checkout Laboratory during the period November 6, 1971 through August 16, 1972. The objective of this activity was to provide an OWS that had been checked out and calibrated to an extent consistent with the ambient one-g environment and provide an OWS acceptable for planned, integrated cluster system testing at the KSC. Checkout was performed using flight hardware within the constraints of hardware availability. Detail test requirements acceptance criteria and operational constraints were provided in the OWS-1 Test and Checkout Requirements, Specifications and Criteria.

Checkout was initiated with the start of continuity/compatibility testing and continued through completion of the All Systems Test (AST), EMC, and residual subsystem retests. During the checkout period, all subsystems, C²F² and the AST, and EMC tests were performed.

The spacecraft was moved from Tower 6 to Tower 2 (KSC) on August 16, 1972. The significant Tower 2 checkout activities included a mercury certification of the habitation area and calibration of the meteoroid shield strain gauges. Mercury certification checks were conducted to demonstrate compliance with program standards.

Major manufacturing activity in Tower 2 was focused on modification of the meteoroid shield and clean-up activities associated with final inspection. All items associated with open work were noted except for crew comments that did not involve hardware changes.

(1) Crew Compartment Fit and Function. Crew system personnel at MDAC-WD performed mission crew tasks in the subsystem tests to verify the crew interfaces. The checkout tests performed in the crew systems area were:

- Food Management
- Crew Accommodations
- Microbial Control Test Sample
- Crew Compartment Fit and Function (C²F²)
- Delta C²F²

No significant problems were encountered during checkout.

The flight crew performed the C²F² test in two sessions and a final bench check of the ring stowage contained on August 30, 1972. Fifteen flight crewmen participated during these tests. There were no significant problems; however, a number of test problem reports were transferred to KSC to be worked off in subsequent delta C²F²s.

(2) Stowage. The OWS stowage subsystems provided for containment/restraint or loose equipment during the launch/boost and in-orbit phases. Stowage provisions consisted of containers, lockers, cabinets, film vaults, food freezers/chillers, and miscellaneous restraint provisions. Checkout for the Stowage Subsystem consisted of a stowage procedure, plus 18 additional procedures, for experiment and water subsystem hardware.

All stowage locations were fit-checked during checkout at MDAC-WD except for 28 locations that were completed at KSC when the hardware became available. In addition, 96 locations were unstowed and the hardware was returned to the suppliers for rework, repair, test, etc., in accordance with contractual direction. Twenty-five ring containers were delivered to KSC. Fourteen of the ring containers were fully stowed and five were partially stowed.

(3) Experiments. The Experiments Subsystem consisted of the hardware accommodations needed to integrate the experiment equipment in the OWS. The accommodations included structural attachments, electrical cabling, pressurization, and vacuum plumbing provisions, and storage restraints.

The experiment/OWS interface accommodations were verified through a series of subsystem tests and the AST. Additional man/machine interface verifications were accomplished during C²F² testing. The subsystem testing and C²F² for experiments covered the period February through August 1972.

No significant problems regarding OWS experiment accommodations were encountered during OWS testing. The significant checkout open items

remaining were summarized in the PDTR. Most of these items were open because the flight hardware was not available for checkout, or the hardware was scheduled for modifications before delivery to KSC.

b. Multiple Docking Adapter

(1) Crew Compartment Fit and Function. The C²F² test was held in December 1971 at MMC. Three flight crewmen and three backup crewmen participated in the tests. The most significant hardware changes that evolved from the test were adding captive screws, addition/modification of Velcro, stowage relocation of an S056 magazine to reduce interference, and the extension of inflight stowage straps to ease operational access. The intent of this test was to have a total C²F² with items not accomplished at Denver to be tested in delta C²F² tests at MDAC-ED and KSC.

(2) Stowage. As discussed in the preceding section, a stowage procedure was used to aid the C²F² test. The procedure was developed during earlier crew reviews and vehicle development tests. The procedure directly supported C²F² test, because most C²F² items were also MDA stowage items.

c. Airlock Module

(1) Crew Compartment Fit and Function. The C²F² began in December 1971 and continued after hard mate with the MDA. Most of the test was accomplished as a combined AM/MDA C²F² in June 1972. As with all C²F² tests, a bench review was conducted before the test and available stowage items were displayed on tables for the astronauts to review.

A C²F² of the AM/MDA was also accomplished at "altitude" during the altitude chamber test. This test revealed a potential problem when Mosites, a closed cell foam, expanded when exposed to a partial vacuum. This resulted in high retention forces on stowed items and in higher forces being required to close covers on foam-lined containers. Use of thinner Mosites and careful tolerance control was instrumental in resolving the Mosites expansion problem.

Other significant changes that evolved from testing at MDAC-ED included the securing of washers to bolts designed for inflight removal, changing the mounting hardware for the TV input station and video switch, adding a 1/16-inch socket head wrench to the MDA tool kit and adding additional restraints to the miscellaneous stowage container.

(2) Stowage. Procedures for the limited stowage operations for the AM were developed during earlier C²F² and Altitude Chamber tests at MDAC-ED.

d. Apollo Telescope Mount

(1) Crew Compartment Fit and Function. The ATM C²F² was successfully completed at MSFC in May 1972.

(2) Stowage. No permanent stowage locations existed on the ATM.

e. John F. Kennedy Space Center

(1) Crew Compartment Fit and Function. The C²F² at KSC was performed to accomplish the verification of fit check and functional sequences not satisfied during the first C²F² tests at MDAC-WD MMC, Denver, and MDAC-ED. Six procedure change requests (PCRs) were written due to OWS stowage changes. Three bench reviews were conducted with crew participation and all components or representative samples were reviewed. There were 1255 deviations written and 231 Interim Discrepancy Reports generated on OWS hardware during the total test run. None of these were major problems and all were closed or upgraded to Discrepancy Reports. All test objectives of the OWS sequence were satisfied.

The final KSC C²F² was held in April 1973 for the AM/MDA/ATM portion. Before the test, all available FCE and experiment hardware available at KSC was launch stowed in accordance with MDA stowage procedures.

At the conclusion of the test, 13 discrepancies were recorded. Three hardware changes were required and consisted of removing the blue paint from the ATM handrail due to chipping, stowage configuration changes for EREP attenuators, and MDA tool kit launch pip pins.

(2) Experiment Accommodation System. Experiment testing was conducted both off-module and on-module. All test requirements were satisfied, with four waivers accepting the remaining discrepant items.

(3) Stowage. All stowage hardware was fit checked and approved for each individual module fit check matrix before vehicle launch. Crew equipment stowage tests began on March 25, 1973 and were completed on April 2, 1973. Test objectives were:

(a) To provide instructions for handling and pre-packaging flight crew equipment in the cleanroom to support subsystem testing, bench review, crew fit and function test, and flight stowage;

(b) To provide instructions for stowage of FCE in the spacecraft for C²F² and flight, and

(c) To create an installation record of stowed FCE in support of launch operations.

Stowage of the SWS at KSC was enhanced by the stowage installation drawings supplied by each module contractor. The installation drawings were agreed to at an intercenter meeting on April 22, 1972. The drawings indicated equipment to be installed, mounting details, and all special installation procedures and requirements. The KSC made extensive use of the drawings as engineering authority in the preparation of stowage Test and Checkout Procedures (TCPs). All final delta C²F²s and stowage tests were completed satisfactorily.

6. Mission Support C²F² Tasks. Due to the many "fixes" engineered to repair or enhance the SWS systems, C²F² activity was used through the launch of SL-4. The following items represent major fit and functional tasks performed on backup units and development hardware.

a. Orbital Workshop

- Wardroom window drying hose fittings and hose assemblies.
- Lower leg restraint and adapter for waste management compartment.
- Adapter 1B96363-AN2D-B01 panel to quick disconnect for Coolanol servicing.
- Waste management compartment restraint.
- Hardware for the thermal shield problem.

b. Multiple Docking Adapter

- Experiment S082 timer cable.
- ATM TV bus redundancy modules and cables.
- Rate gyro six-pack installation.
- High torque screw removal tool.

c. Airlock Module

- Coolant reservicing kit.
- Rate gyro six-pack cabling on truss assembly (EVA).

7. Inflight Maintenance (IFM). Spacecraft design before Skylab employed highly reliable equipment and redundant systems to insure mission success. Missions were of relative short duration and payload weight and volume were critical. Because of these factors, an inflight maintenance capability was neither considered nor required. Early Skylab design was based on maximum use of proven Apollo and Gemini hardware and excluded inflight maintenance as a requirement. However, this philosophy gradually changed throughout the program, evolving from a minimum maintenance concept of one of extensive planning and provisioning of inflight maintenance support.

The initial inflight maintenance planning involved provisioning of spares and tools for maintenance support of only critical single failure point items. The scope of inflight maintenance support was later expanded to include all hardware that could affect the crew or mission objectives if failure occurred. An extensive design and hardware analysis was initiated to determine the maintenance capability necessary to support the mission. Because of limited payload weight and volume each spare and tool was evaluated and the need justified, based on the effects of failure, before stowage on board Skylab was approved. The result was a high level of maintenance capability tailored to identifiable hardware failures with the greatest potential of occurrence. This maintenance philosophy proved to be a disadvantage during the Skylab missions because it did not provide a good general maintenance capability. Items such as a full range of sockets and wrenches, a multimeter, drills, files and a hacksaw could not be justified because specific needs could not be identified. As a consequence, many needed tools were not placed on board.

a. Scheduled IFM. Scheduled IFM activities were held to a minimum to conserve crew time. Requirements were established only where periodic cleaning or replacement of consumable, cycle-sensitive or time-sensitive items were necessary. The requirements were included in the checklists as part of the normal housekeeping tasks. Performance of the tasks were controlled by the flight plan and scheduled to accommodate crew workload. During the mission, the frequency of vacuum cleaning the ECS fan inlet screens was changed from 7 to 2 days because of the unanticipated large amount of debris that they collected. Scheduled vacuum cleaning of the OWS Heat Exchanger vanes every 6 days was a task initiated during SL-4 to remove water and particulate material build-up which reduced the heat exchanger efficiency. Replacement of the Urine Separator filters was to have been accomplished every 28 days but was found to be unnecessary and was performed only at the end of each mission when the Urine Separators were replaced.

b. Unscheduled IFM. Unscheduled IFM capability was provided on board the SWS for the purpose of replacing failed components, installing auxiliary and backup hardware, and equipment servicing and repair. The capability was provided in the form of spares, tools, and procedures for performing 160 different unscheduled tasks. Included were replacement of ECS fans, tape recorders, teleprinter, lights, fire sensors, speaker intercom assemblies etc. Repair of ECS ducts, structural leakage, shoe indexing cleats etc., and installation of auxiliary hardware such as contingency power and TV system cables. Experiment S192 Attenuator and S054 Shutter Override Actuator were incorporated in the unscheduled maintenance planning. Additional capability was included for contingency opening of hatches and experiment doors. During the Skylab missions, 33 such tasks were performed and many of the tasks such as replacement of the tape recorders were performed a number of times.

c. Contingency IFM. In addition to the capability provided for scheduled and unscheduled inflight maintenance, tools and materials were placed on board Skylab to provide some general maintenance capability. The capability was provided to permit repair of failed equipment for which no specific inflight maintenance activity was anticipated. Items such as tape, wire, C-clamps, various types of pliers, a vise, twine, hammers, and tweezers were included in the Skylab tool inventory for this purpose.

Additional maintenance tools and equipment were launched on board the three CSMs to provide capability to correct equipment malfunctions that were unanticipated. Deployment of the Skylab Parasol, the OWS Solar Wing, and the Twin Pole Solar Sail, repair of the S019 Extension Mechanism, installation of the Rate Gyro Six Pack and S082B Auxiliary Timer, and replacement of the ATM TV Monitor were just a few such tasks performed. These were tasks for which on board maintenance support was inadequate.

Other contingencies such as failure of CBRM 15, binding of the ATM door ramp latches, leakage of the condensate and Coolanol systems and contamination in the ATM C&D coolant loop developed during the missions. These maintenance actions were performed using the onboard support equipment. Procedures were developed real-time and uplinked to the crew.

d. Tools and Equipment. The tools and equipment onboard Skylab were provided to support not only inflight maintenance, but also activation, operation, and deactivation of the Cluster systems and experiments. Lubricants, safety wire, twine, tape, Velcro and other like materials were included for general use throughout the cluster and for contingency maintenance. Spare tools were provided in some instances where justified by the number of applications and susceptibility to loss or breakage.

The tool/maintenance equipment complement onboard Skylab was primarily contained in five kits located throughout the SWS. Tool Kits 1 and 2 located in the OWS stowage lockers, E623 and E624 contained most of the tools and materials required for maintenance. An Activation/Contingency Tool Kit located in the MDA locker M144 contained tools and materials which were required or potentially needed during periods when the tool kits in the OWS were not accessible as before OWS activation and during EVA. Some duplicate tools were included for use during activation when the same tool was simultaneously required by two crewmen. The Hatch Tool Kit located on the forward side of the MDA Axial Docking Port Hatch contained the tools required to disassemble the hatch in the event that the latching mechanism became jammed. The repair kit located in the OWS locker E620 contained materials necessary to patch leaks in the habitation area of the cluster and miscellaneous fastening materials and devices such as tape, Velcro, and snap assemblies.

Additional special purpose tool kits, tools, materials and equipment were located at various places in the spacecraft. These included the CSM Tool Kit, S190 Tools, EMU and PGA Maintenance Kits, Water System Servicing Equipment, and spare tools plus a number of miscellaneous tools and maintenance equipment items.

The Skylab tool/maintenance equipment inventory was supplemented on all three missions with items necessary to install auxiliary hardware, support contingency inflight maintenance, and replace tools that were lost or broken during previous missions.

A complete and detailed evaluation of the Skylab IFM activities is included in the MSFC Skylab Crew Systems Mission Evaluation Report (TMX 64825).

8. Conclusions and Recommendations. The role of man throughout the Skylab program provided the necessary insight to assure that man/system interfaces were compatible and practical. From the inception of hardware design concepts, crew system reviews were conducted through all phases of hardware development, system buildup, testing, and finally during operations. Many spacecraft man/systems design requirements were produced and verified during the course of the Skylab program. Throughout the program several man/system requirements were not implemented on a common basis and in the vehicle, which resulted in evaluation comparisons and selection of preferred solutions. A portion of the significant man/system criteria for future spacecraft includes: interior arrangements based on gravity orientation; standard foot restraint capability throughout; simple restraints for covers and onboard equipment; optimized ventilation for gravity substitution work area; translation and stability aids for

EVA to encompass the entire vehicle; initial design of IVA and EVA in-flight maintenance to include provisions for standard tools, spares and work area, and from inception through mission support, a high fidelity crew systems mockup to evaluate crew interfaces, layout, workstations, and operational procedures.

Recognizing that the Skylab experience leads to improved future systems, the document "Man/System Design Criteria for Manned Orbiting Payloads," MSFC-STD-512, is specifically directed to the man/system design questions that are likely to be asked during the course of future program development.

The cumulative effect of NASA and contractor crew system personnel together with the astronauts' influence contributed significantly to the Skylab cluster design. When the crew system design changes are considered individually, it is difficult to conclude that any single change made an appreciable difference between success or failure of a specific mission task; however, the cumulative inputs increased the workability of Skylab, saved time in task performance, and most importantly gave the astronauts the interior arrangement and man/system interfaces necessary to mission success. This supports the conclusion that man/system integration must be an integral part of future manned programs from program inception through mission support.

M. Thermal Control/Environmental Control System

The thermal and environmental control systems changed considerably from program inception to the as-flown configuration. The most significant, Thermal Control System/Environmental Control System (TCS/ECS) changes occurred with the change from the Saturn I WWS to the Saturn II DWS configuration and corresponding changes to program philosophies. The OWS TCS originally was to provide a habitable environment for the Habitability/Crew Quarters Experiment (M487). The OWS was also to have been an operational S-IVB upper stage fully loaded with liquid oxygen and hydrogen, which were burned on orbital insertion. After the residual propellants were vented and the compartments were pressurized, the crew was to carry in and install fans and other system components in the OWS that were not compatible with liquid hydrogen. As a result, the initial OWS system had to be simple, preinstalled before launch, and require a minimum effort for activation. The design was therefore primarily passively controlled with suitable insulation and coatings and also had fans with cloth ducts on the sidewalls for additional temperature control. To meet the early launch date, all of the vehicles that composed the cluster (including a LM vehicle) had to use essentially off-the-shelf TCS and ECS hardware and each vehicle was expected to provide its own thermal control. Oxygen and nitrogen was provided from the CSM and Carbon Dioxide (CO₂) and water vapor was removed by the AM system.

As the launch date was rescheduled, the entire concept was changed to the Saturn V DWS configuration (without a LM vehicle) in which the workshop was launched without propellants and all hardware was installed inside before launch. All the Skylab TCS/ECS systems were allowed to become more sophisticated at this time because the launch data was extended long enough to qualify new hardware. Also, the philosophy of each vehicle providing its own thermal control was dropped and the Skylab TCS/ECS systems were integrated into one overall system with central control in the AM.

The metabolic heat load was originally based on the assumption that only two men would be in the cluster for the CSM was always to be manned. The flight also was originally to have included only two missions. The first mission was to be flown with the X-axis perpendicular to the orbit plane with movable solar arrays on the OWS to maintain the active side facing the sun. The second mission was to be flown in the solar inertial attitude. The beta angle was to vary between 0 ± 53.5 degrees. The following paragraphs briefly describe the evolution of the systems resulting from many changes to these original program requirements and development problems.

1. Atmospheric Control System

a. Carbon Dioxide Control and Odor Removal. The cluster CO₂ and odor removal system was originally supplied by Gemini lithium hydroxide (LiOH) canisters, which had a 14-day capacity for two men and were to be replaced in flight (see Figure II.M-1). Some spare cartridges could have been launched on the AM, but most were resupplied by the CSMs. The molecular sieve was to be carried in the cluster as an experiment. The sieve

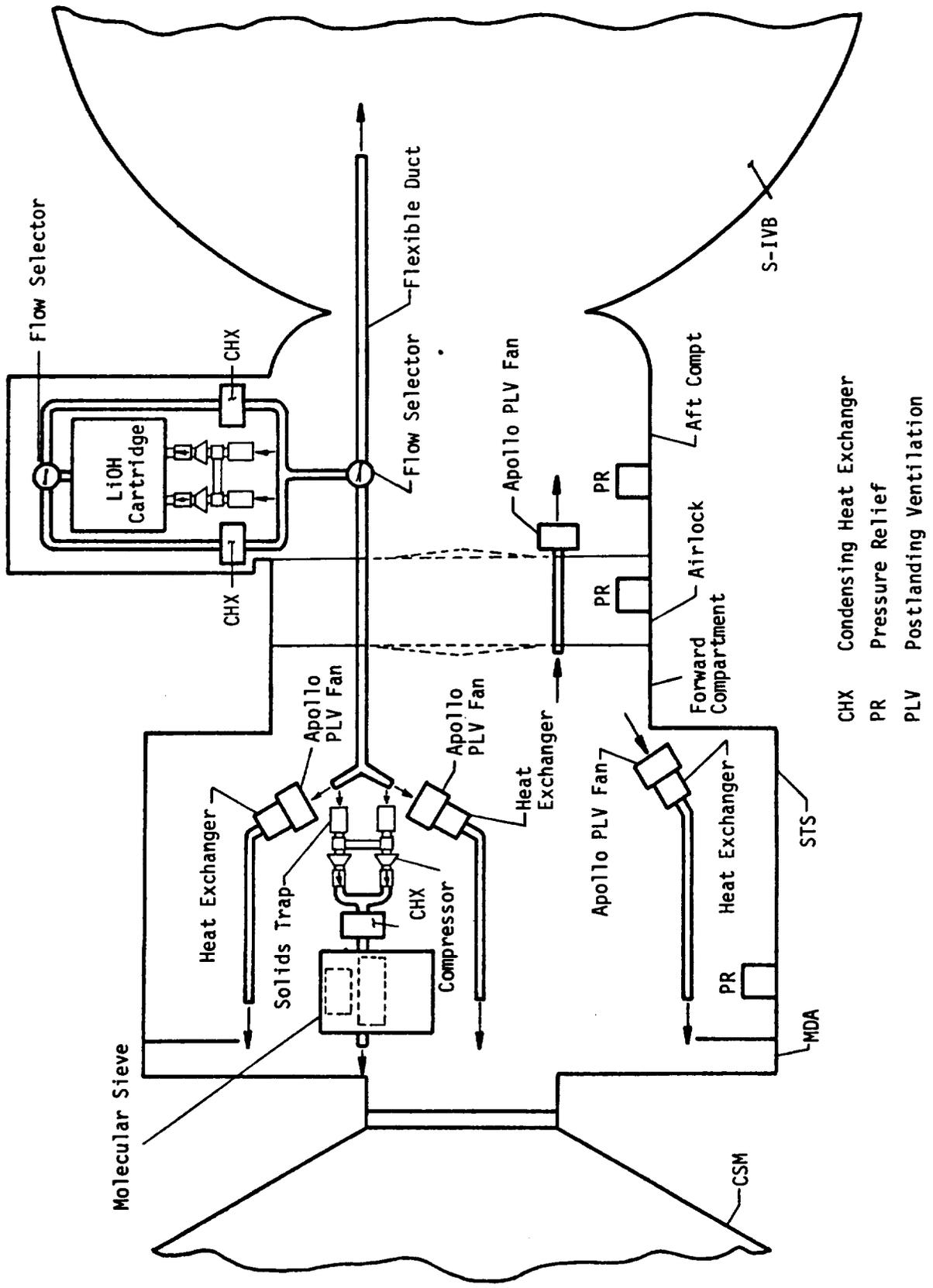


Figure II.M-1 Atmospheric Purification System

originally served as a backup for the LiOH system and later as a prime system with the LiOH as the backup system for missions longer than 28 days. The LiOH system was eventually dropped and a second molecular sieve was added with both sieves to be installed in the AM. These changes took place before the establishment of the Saturn V DWS configuration when the CO₂ partial pressure requirement was 7.6 mmHg. After the DWS was baselined, the CO₂ partial pressure requirement was reduced to a value of 5.5 mmHg. To accommodate the new requirement, the flowrate through the adsorbent canisters was increased from 10 lb/hour to 15.5 lb/hour.

A concern over possible contamination of external optical surfaces by exhaust gases from the molecular sieves during bed desorpting resulted in a directive to relocate the molecular sieve overboard exhaust ducts. As a result, both molecular sieve overboard ducts were combined and relocated to exhaust from a single outlet from the side opposite the optics.

b. Humidity Control. Humidity was originally to be controlled by one of two condensing heat exchangers with a coolant input temperature of 40°F; however, the capability to maintain the cluster dewpoint above the minimum 46°F allowable was marginal with a 40°F control valve system and the problem was aggravated by the required molecular sieve flow increase because more atmospheric moisture was adsorbed and dumped overboard by the molecular sieve. However, this problem was ultimately solved by increasing the coolant temperature entering the condensing heat exchangers from 40 to 47°F, thus raising the atmosphere dewpoint by reducing the amount of moisture condensed in the heat exchangers. The original Gemini temperature control valves were replaced by off-the-shelf valves of a different design, but modified to control coolant temperature of 47°F. This change was accomplished simultaneously with that required to reduce coolant temperatures delivered to the battery modules.

Concern that dumping condensate overboard might interfere with experiments that required external sightings caused condensate system design changes. Some of these changes are listed below:

- (1) Relocated the AM condensate overboard dump ports on the side opposite the affected optical surfaces.
- (2) Provided the capability to dump condensate from the AM storage tank to the OWS waste tank, which also was modified to preclude release of water or ice particles of sufficient size to contaminate the optics.
- (3) Modified the AM dump ports to include restricted outlets that would cause a more predictable exhaust plume profile.
- (4) Provided capability to transfer condensate directly from the AM condensing heat exchangers to an evacuated condensate holding tank (a modified OWS waste tank) located in the OWS. The condensate was to be stored in the holding tank and subsequently dumped to the OWS waste tank.

This change resulted from water freezing at the OWS waste tank dump probe. Freezing was encountered during tests simulating condensate transfer from the AM storage tank to the OWS waste tank. The OWS dump probe was also modified to permit dumping from the AM condensate tank to the OWS waste tank. However, transfer to the OWS holding tank was retained as the primary method because the larger volume of the holding tank allowed a longer period of time between dump operations.

A design requirement change was made relatively late in the program to provide a positive means for inflight servicing of the condensing heat exchanger water separator plates. The change was prompted by the concern that the plates might dry out during low water generation rate periods of the mission and by uncertainties associated with the previously baselined self-wetting method. The new method had the advantage of being a straightforward step-by-step process that assured positive plate wetting. Although the self-wetting approach had proved satisfactory during development testing, and required fewer operational steps, its success inflight would depend strongly on cluster dewpoint and proper crew attention. The self-wetting technique was sensitive to both free water carryover to the molecular sieves and gas carryover to the condensate collection system.

The final configuration of the condensate control system is shown in Figure II.M-2.

2. Ventilation System. The AM ventilation system originally used Gemini cabin fans that were later replaced by GFE Apollo Postlanding Ventilation (PLV) fans. Advantages of the PLV fans were that (a) they needed no ac-dc power inverter, (b) required less power, and (c) it standardized fans throughout the cluster for PLV fans were also used in the MDA and OWS; however, the PLV fans had undesirable flow/delta P characteristics for use in conjunction with the cabin heat exchangers. The lack of pressure head from the PLV fan necessitated the use of low pressure drop screens and ducting. The inclusion of sound suppression equipment in the fan module designs to satisfy cluster noise level specifications resulted in additional system resistances, which also contributed to the marginal fan characteristics. Alternative fan designs that would provide more desirable flow/delta P characteristics were pursued but a decision was made to retain the PLV fan. The fan performed well during the Skylab missions, but problems were encountered during flight with dust and other particles passing through the coarse (low pressure drop) screens at the inlet to the OWS heat exchangers.

The OWS ventilation system was modified with the change from the Saturn IV WWS to the Saturn V DWS. An additional duct was added to the existing two-duct system to increase the total flow. The diffusers in the WWS configuration were mounted on the ceiling and the equipment was on the floor. In the DWS configuration, the diffusers were mounted on the floor together with various pieces of Skylab equipment. Additional flow was required to maintain an average atmosphere velocity of approximately 40 ft/min because the reversal of the floor and ceiling placed equipment in the vicinity of the diffusers which disrupted their flow pattern. The resulting system performed well.

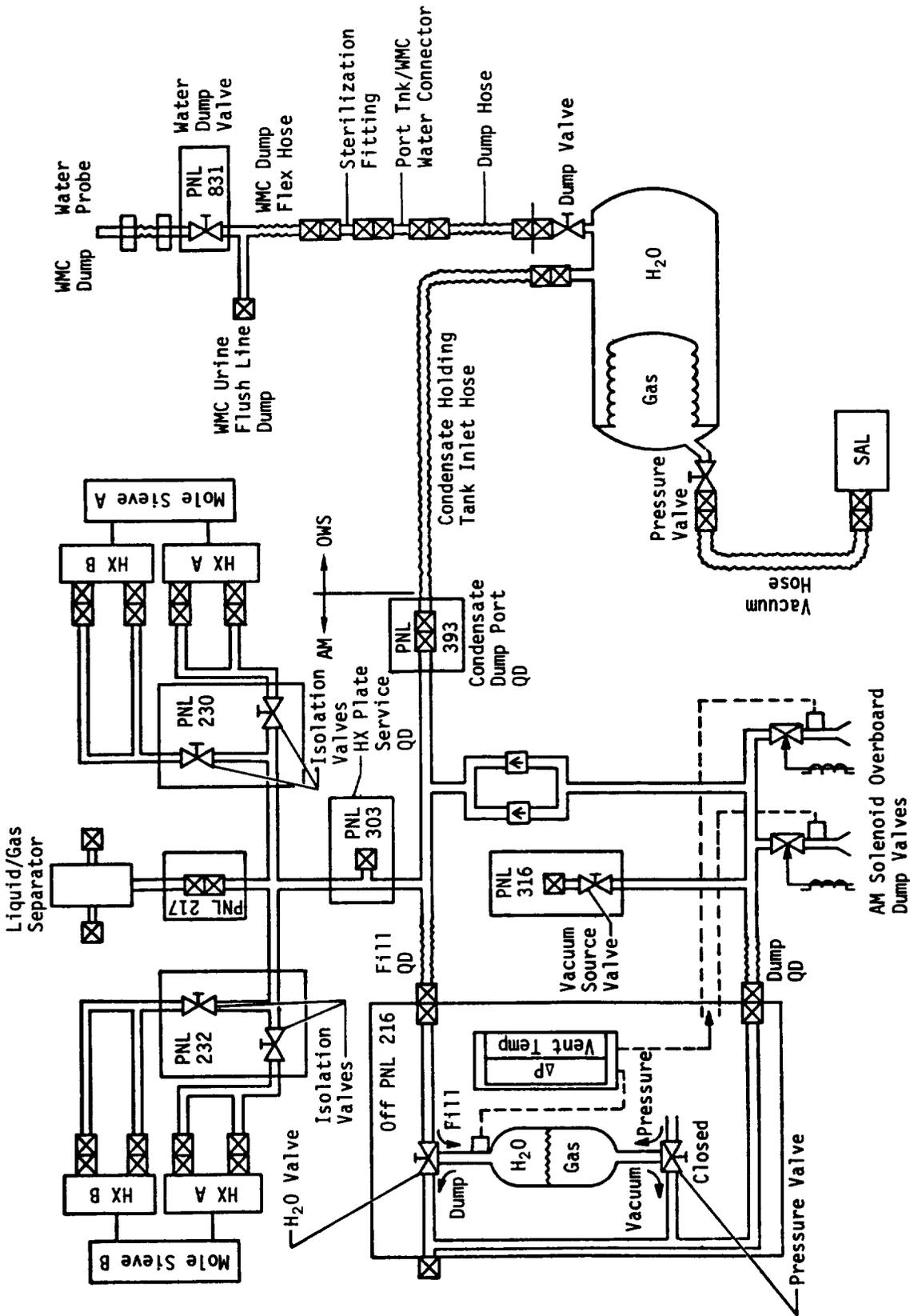


Figure II.M-2 Condensate Control System

3. OWS/AM/MDA Thermal Control System

a. Orbital Workshop. The ECS/TCS as defined for the Saturn I WWS provided control by fan circulated gas in eight evenly-spaced ducts. These ducts were formed by a series of thermal curtains and rails around the periphery of the habitation area as shown in Figure II.M-3. As the atmospheric temperature increased, the duct fans would be activated on the cold side of the vehicle and when it decreased, duct fans would be activated on the hot side. If required, duct heaters would also be turned on to increase the temperature. An automatic control system was provided with manual override to control the fans and heaters. This system gave gas temperatures in the range of approximately 55 to 105°F. A meteoroid shield with a black painted external surface ($\alpha_s/\epsilon = 0.9/0.9$) was assumed with a moderate resistance to heat transfer (no gold) between the meteoroid shield internal surface and the tank wall. The minimum temperature for safe astronaut entry after tank passivation was defined as minus 150°F and no active heaters were provided for warmup from the initial temperature of minus 400°F after the residual hydrogen was vented.

During the latter part of 1967 and in 1968, studies defined the advantages of controlling heat leaks in the tank sidewall, tank joint regions, the forward dome and the plenum region, which included the common bulkhead. These studies led to the gold tape on the tank external surface, the forward dome high performance insulation system, the thermal shields on the external joint areas, and foam insulation in the plenum region, the addition of foam insulation was not implemented, however, until after the change from a WWS to a DWS.

By mid-1969, the system concept and design had undergone many changes. Crew comfort was no longer in the category of an experiment but more stringent requirements were now defined as follows:

Atmospheric Temperature	65 to 75°F
Mean Radiant Wall Temperature	65 to 75°F
Humidity	0.018 Specific (minimum) and 95 % Relative (maximum)
Touch Temperature	55 to 105°F
Atmospheric Velocity	15 to 100 ft/min.

The cloth ducts in the OWS were removed and an "integrated" system was proposed that took maximum advantage of the AM system. The temperatures were to be controlled automatically or manually using cooling delivered from the AM and 750 watts of the 1000 watts of heater power available (500 watt capability in each of two ducts with fan clusters). All major surfaces were to be between 60 and 80°F, but localized surfaces accessible to the crew could be as cold as 55°F or as hot as 105°F. Radiant heaters providing a maximum of 1000 watts were to be used for warmup to provide a 0°F mean internal temperature at pressurization initiation and a 40°F minimum internal temperature by the time tank seal and lighting installation was completed.

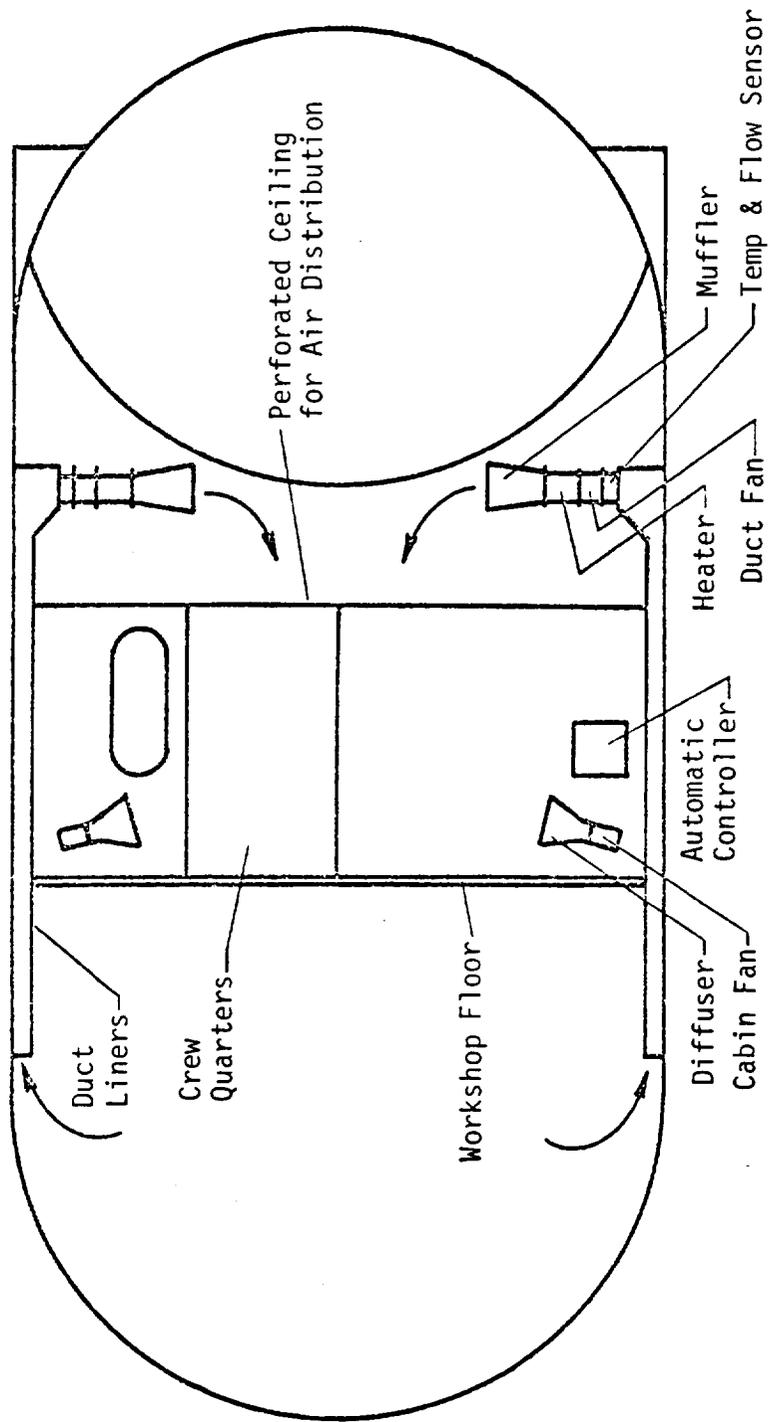


Figure II.M-3 Orbital Workshop Thermal Control System, Schematic View

The WWS requirements were reassessed with the change to a DWS configuration in September 1969. The perpendicular-to-orbit plane attitude was dropped and the missions were to be flown in a solar inertial attitude at an orbital inclination of 30 degrees ($\beta = 53.5$ degrees). Before completion of this assessment, change to a 50 degree orbital inclination ($\beta = 73.5$ degrees). was made in early 1970. This meant the design had to consider the increased heat loads associated with orbits in 100 percent sunlight whereas the maximum previously had been 73 percent sunlight.

OWS performance requirements were changed to include an expanded comfort box (which was the final specification comfort box). A minimum OWS waste heat (housekeeping) load of 250 watts and a maximum metabolic (sensible) load of 1000 Btu/hour (293 watts) were defined. Maximum heater power use for cold conditions was redefined as 825 and 1170 watts for nominal and two sigma conditions, respectively. The minimum electrical waste heat removal was specified as between 600 and 1350 watts, depending on beta angle as well as consideration of nominal and two sigma conditions.

The major design changes that resulted from the preceding requirements were the addition of white paint on the solar-facing side of the OWS meteoroid shield, the addition of 500 watts of manually controlled heater power in the third duct, and foam insulation added in the plenum region to alleviate potential condensation problems and to minimize the heat leak.

In 1971, heat pipes were installed in the workshop to alleviate potential condensation problems in the regions near the floor and ceiling supports, the wall behind the water bottles, the balsa wood forward joint, and the back of the storage freezer in the forward compartment. Also, in this period the AM cooling delivered to the workshop was redefined with a resultant 50 watt decrease in the specified minimum electrical waste heat removal equipment and an increase in the housekeeping load to 400 watts. The AM cooling was again redefined early in 1972 and the minimum housekeeping waste heat load was increased from 400 to 525 watts, which became the final design value. Based on these changes, the white paint pattern on the meteoroid shield external surfaces was finalized in February 1972. No significant design changes were made between this time and SL-1 launch.

b. Airlock Module. In going from the WWS to the DWS configuration, the only significant change made to the AM atmosphere cooling system was installation of four OWS heat exchangers and associated fans to provide more sensible cooling to the OWS. This change was actually made just before conversion to the Saturn V workshop configuration and the heat exchanger fan assemblies were located in the space previously allotted to the LiOH system in the aft AM compartment.

The change in orbit inclination angle from 30 to 50 degrees increased the mission beta angle extremes from ± 53.5 to ± 73.5 degrees. Combined with the change to the basic solar inertial attitude for all missions, this resulted in a more severe hot case external environment design condition. These factors resulted in a change from a multiple layer "superinsulation" concept to the thermal curtain insulation design for the AM.

c. Multiple Docking Adapter. The evolution of the thermal control systems in the MDA involved primarily refinements to the insulation

and heater control systems. A heater system was also developed for the S190 window, which was added with the EREP experiments.

d. Final Cluster Thermal Control System. The final configuration of the thermal control systems for the cluster is shown in Figures II.M-4 and II.M-5.

4. Gas Supply System. The initial requirements were to store and supply O_2 at sufficient quantities and flowrates for initial pressurization, for replenishment of atmospheric leakage, and for metabolic consumption by three crewmen for a 30-day mission and to provide O_2 and H_2 for the CSM fuel cell. The cluster atmosphere was to be 5 psia O_2 . To store the required O_2 and hydrogen (H_2) modified Gemini O_2 and H_2 cryogenic tanks were mounted on AM trusses. Thermostatically-controlled calrod heaters, installed on the lines downstream of the cryogenic tanks, warmed the gases supplied to the distribution system. Two 120 psig Gemini pressure regulators provided O_2 supply and pressure control.

As the WWS design was firmed up, the cryogenic tanks were removed from the AM. O_2 and N_2 were then supplied from the CSM for a two-gas atmosphere. The mainline Apollo CSMs carried two cryogenic O_2 tanks (changed to three tanks following the Apollo 13 mission) amounting to a total usable load of 640 pounds and two cryogenic H_2 tanks amounting to a total usable load of 56 pounds. The tanks were qualified to support mission durations of up to 14 days, although the cryogens could last for approximately another week. For the planned 28-day and 56-day missions of Skylab, these tanks would be replaced in the SM by three cryogenic O_2 tanks with a total usable capacity of 3600 pounds, three cryogenic H_2 tanks with a total usable capacity of 225 pounds, and one cryogenic Nitrogen (N_2) tank with a total usable capacity of 850 pounds. These tanks were to be qualified to support a mission of at least 56 days duration with the capability of later being qualified to support 90 day missions. The H_2 tanks on both the Apollo mission CSMs and on the extended duration Skylab CSMs were provided to supply H_2 for fuel cell operation. Almost all the water in the original Skylab concepts was to be supplied by fuel cell operation.

In addition to the main cryogenic gas supply on the CSM, two high pressure gaseous O_2 tanks (LM descent tanks, 2250 psia) were carried externally on the AM to supply high O_2 flow rates for the maneuvering equipment experiments (M509/T020) and for EVAs. After depletion by use to below 1000 psia, these tanks were to serve as accumulators and would be kept recharged with O_2 from the CSM.

The cluster total pressure and O_2 partial pressure were initially maintained by the cabin pressure regulator in the CSM. Figure II.M-6 presents a schematic of the CSM O_2/N_2 control system. Two series N_2 solenoid valves were used to shut off N_2 flowing to the cabin pressure regulator, each controlled by its own controller. An N_2 selector valve was used to provide N_2 to the two-gas control system, or to the rest of the O_2/N_2 system. Both O_2 and N_2 could be delivered via an umbilical and Quick Disconnect (QD) from the CSM to the MDA and back to the rest of the cluster as

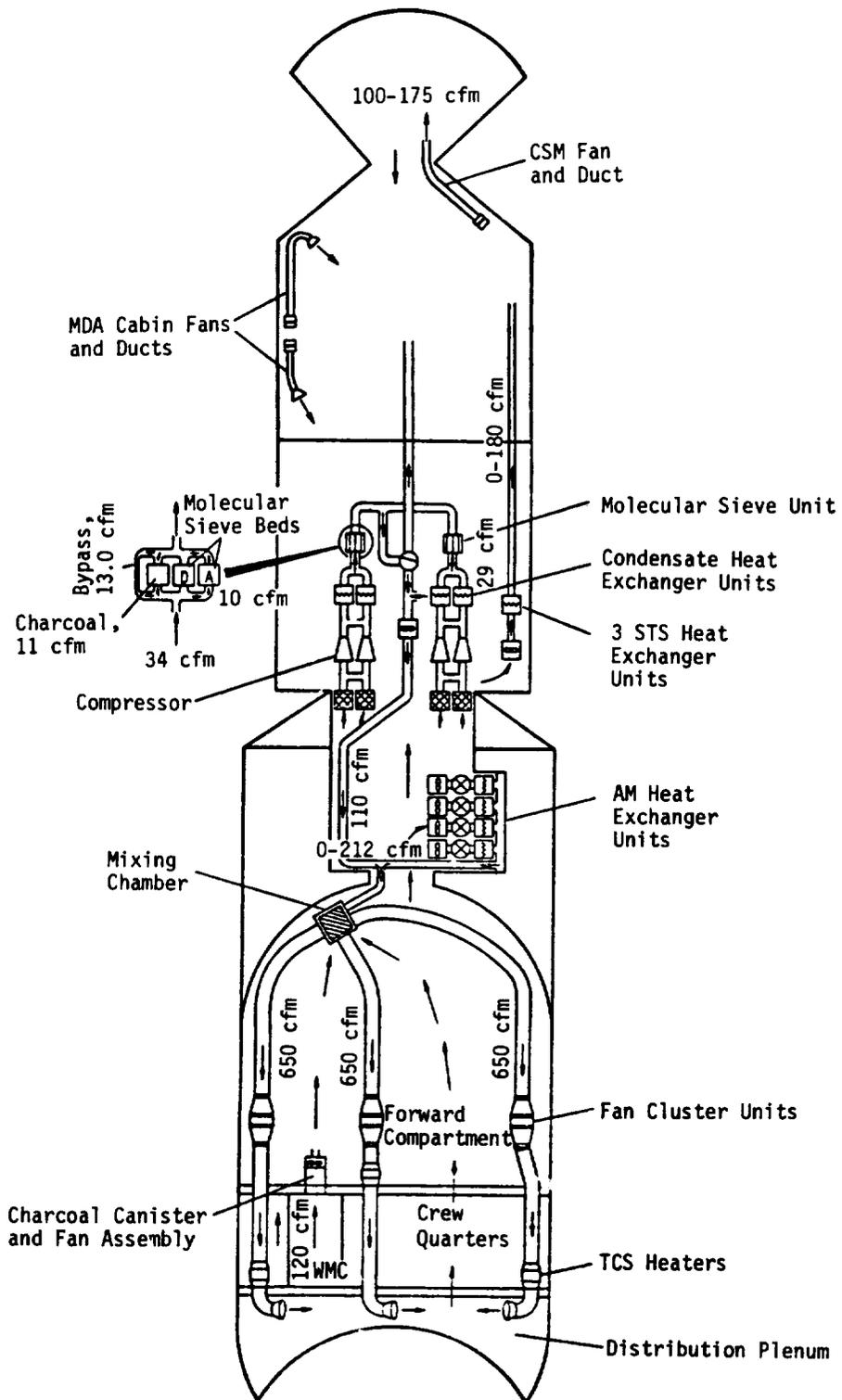


Figure II.M-4 Skylab Cluster Thermal Control System

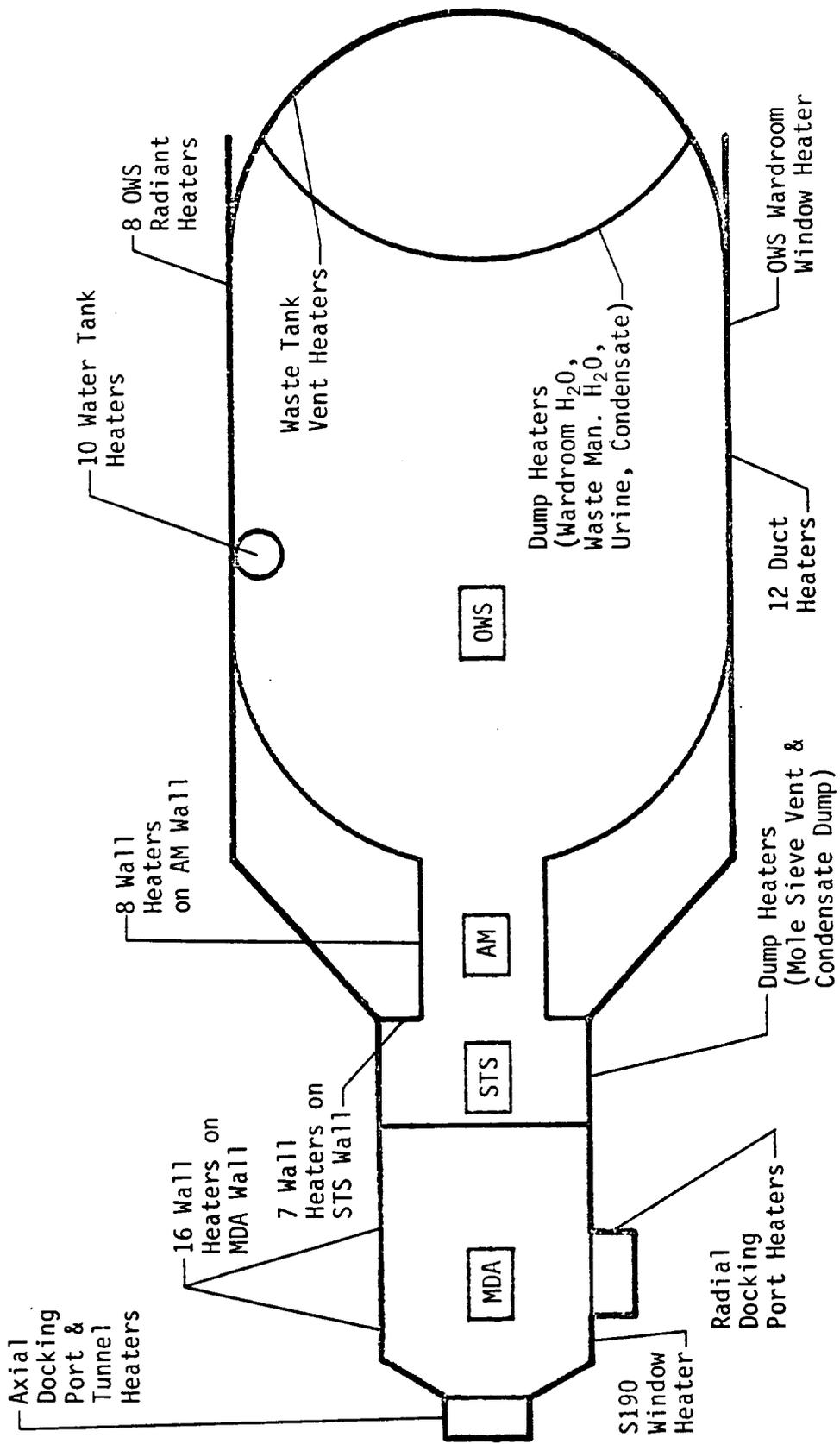


Figure II.M-5 Skylab Heater Locations

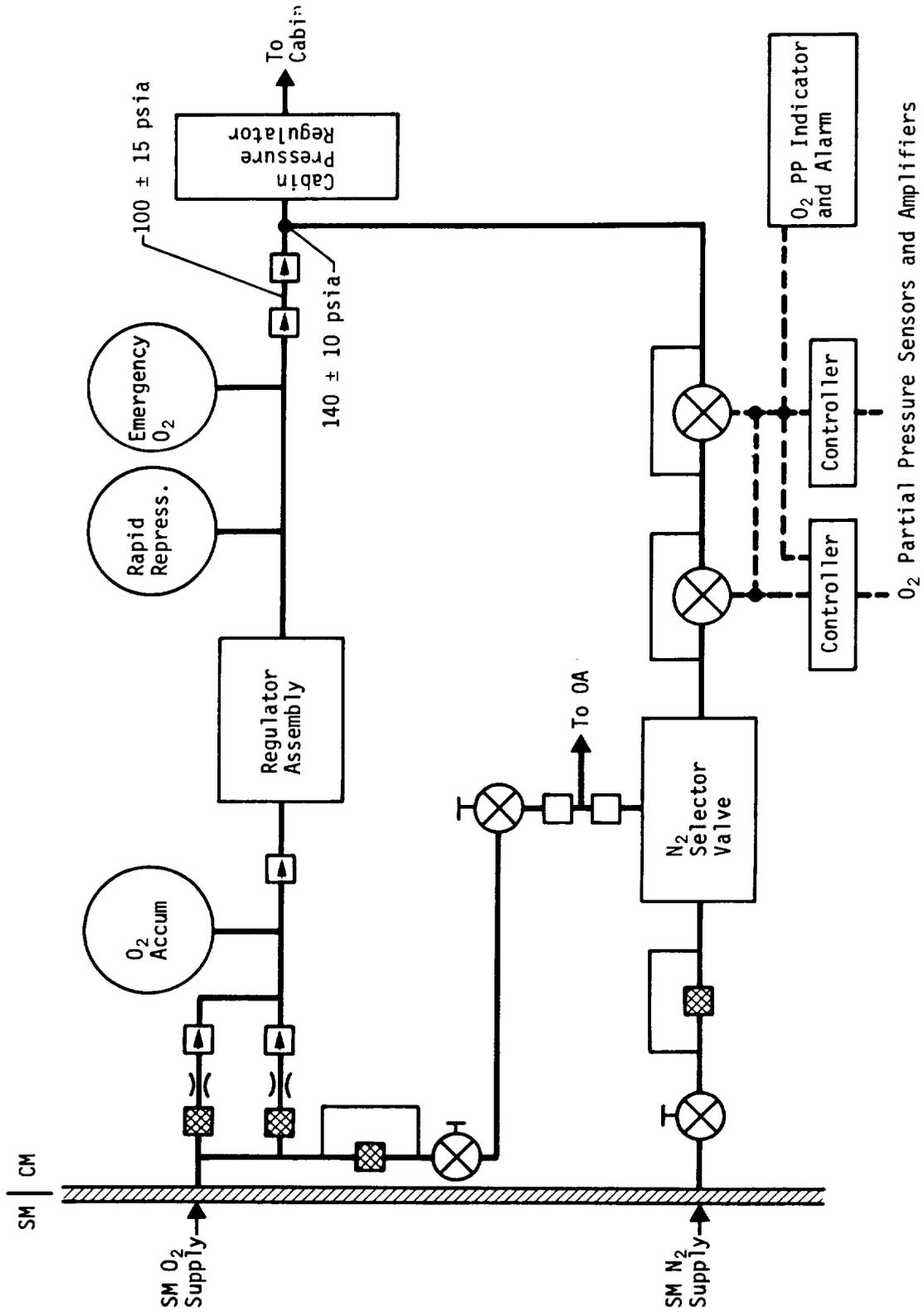


Figure II.M-6 Simplified CSM Atmospheric Control System Schematic

shown in Figure II.M-7. Nitrogen would be supplied for initial pressurization and then the system would be purged of N₂. Oxygen would be supplied for EVA/IVA operations and for the mole sieve pneumatics.

Two O₂ regulators were located on the AM; a 120 psi regulator for normal use and a 240 psi regulator for M509/T020 gas use.

In addition to the other O₂/N₂ subsystems, there were provisions to supply O₂ to and from the LM. Provisions in the LM were also provided for independent operation involving EVAs conducted from the LM.

Changeover to the DWS with the Saturn V booster permitted a larger allowable launch weight. Consequently direction was given to store all O₂ and N₂ supplies required for the Skylab mission onboard the AM. Storage of the O₂ and N₂ as high pressure gases was selected over cryogenic storage because of lower cost, lower development risks, ease of servicing, and more operational flexibility for the multimission Skylab program.

The CSM was to remain a baseline Apollo Block II CSM with only a few changes. Only two cryo O₂ tanks were to be carried, instead of the three as flown on the later Apollo missions. A high-flow EVA/IVA station was added to permit an IVA or EVA from the CSM using only O₂. A polychoke orifice was added to the system to allow boil-off of cryogenic O₂ to be added to the cluster atmosphere.

All the gas that had been carried in the extended duration cryogen tanks in the SM for the cluster was placed in high pressure gaseous O₂ and N₂ tanks on the exterior of the AM. There were initially six O₂ tanks and five N₂ tanks (3000 psia), although a sixth N₂ tank was added later to provide usable capacities of 4930 pounds O₂ and 1320 pounds N₂. The main power source for the Skylab missions was changed from fuel cells to solar cells. No extra H₂ was carried to run the fuel cells.

Additional changes in design requirements that reflected on the system design during this time are listed below:

- a. Requirement for both DCS ground command capability and on-board control of O₂ and N₂ flow.
- b. Removal of the provisions to transfer O₂/N₂ gas via an umbilical and QD from the CSM to the MDA.
- c. Addition of the automatic two-gas atmosphere control system to the AM including the addition of two 5 psia cabin pressure regulators.
- d. Addition of two 150 psig N₂ regulators in the AM to regulate N₂ coming into the cluster.
- e. Requirement for ten OWS water tanks containing a total of 6000 pounds of usable water due to the decision to supply all power for the cluster from solar cells, not from the CSM fuel cells. Along with this requirement came the requirement for two 35 psig N₂ regulators in the OWS (supplied from the AM) to pressurize the yellows in the water tanks.

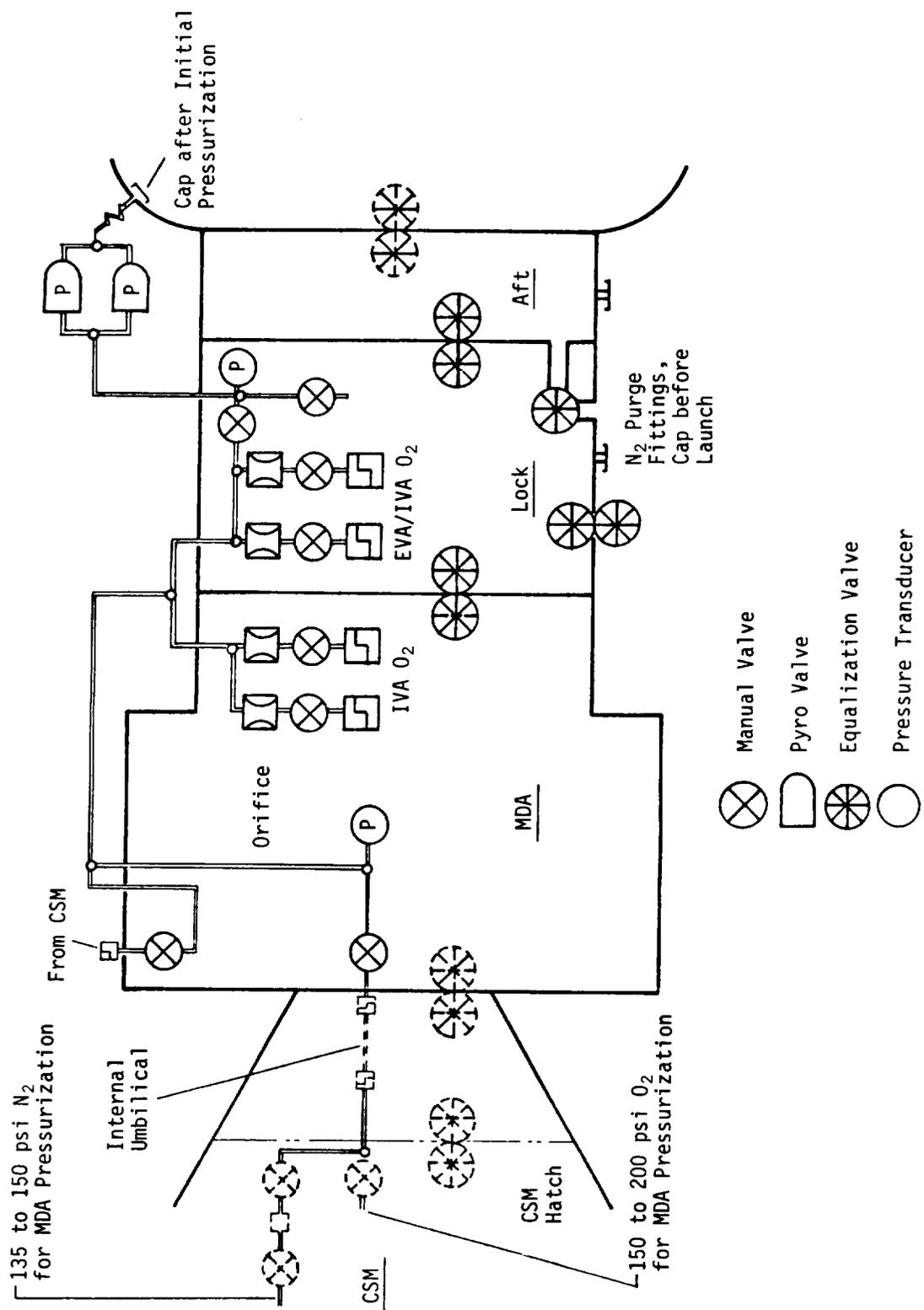


Figure II.M-7 Atmospheric and EVA/IVA Air Distribution System

- f. Requirement for supplying N₂ to the OWS for biomedical experiments.
- g. Requirement to supply N₂ instead of O₂ to the mole sieve pneumatic valves.
- h. Requirement to supply two 5 psia N₂ regulators to pressurize reservoirs in the Suit Umbilical System (SUS) cooling loop and the ATM C&D cooling loop systems.
- i. Conversion of the M509 propulsion gas from O₂ to N₂. Addition of three high-pressure (3000 psia) N₂ tanks (containing 10 pounds each) to the cluster for the M509 experiment. Addition of an N₂ recharge station in the AM for inflight servicing of the M509 N₂ tanks.

Changes were later required in the controlling range of the two-gas control system. The O₂ partial pressure control range requirement of the two-gas control system was initially 3.7 ± 0.2 psia. It was determined by system analyses that this range could not be consistently achieved, based on the assumption of stacking maximum specification tolerances of the PO₂ sensor/amplifier assembly and the maximum specification deadband tolerances of the O₂/N₂ controller. In addition, there was the potential for overlap of the PO₂ control band and the C&W alarm band, again based on maximum tolerance stackup. The sensor/amplifier specification tolerances were based on extreme ranges of temperature (40 to 90°F) and O₂ partial pressure (0 to 6.4 psia) in addition to further allowances for test instrumentation errors and long term drift effects. Subsequent analyses using test data applicable to a more realistic temperature range (60 to 90°F) and O₂ partial pressure range (2.8 to 3.9 psia) still showed a potential problem of consistently meeting the 3.7 ± 0.2 psia requirement.

A reevaluation of cluster O₂ partial pressure limits during this time, resulted in a system PO₂ requirement change to 3.6 ± 0.3 psia. It was determined that this new requirement could be met by limiting the sensor/amplifier full-scale inaccuracy to ± 3 percent and by readjustment of the O₂/N₂ controller trip points. Accordingly, steps were taken to improve sensor temperature compensation so that worst case sensor/amplifier inaccuracy was 3 percent or less within the PO₂ range of 2.8 to 3.9 psia and temperature range of 60 to 90°F. Also, the controllers were changed by adjusting the lower trip point to minimize control band width and adjusting the upper trip point to center the band width around a nominal 3.6 psia O₂ partial pressure. The final O₂/N₂ gas supply system is shown in Figure II.M-8.

5. Depressurization System

a. Waste Tank Vent. The waste tank concept originated in the days of the WWS. The original plan was to dispose of urine by dumping it overboard through a fitting installed by the crew in the side of the fuel tank. When tests revealed that this would be detrimental to the solar arrays, it was decided to have the crew punch a hole in the common bulkhead and install a heated dump probe so that urine could be dumped into

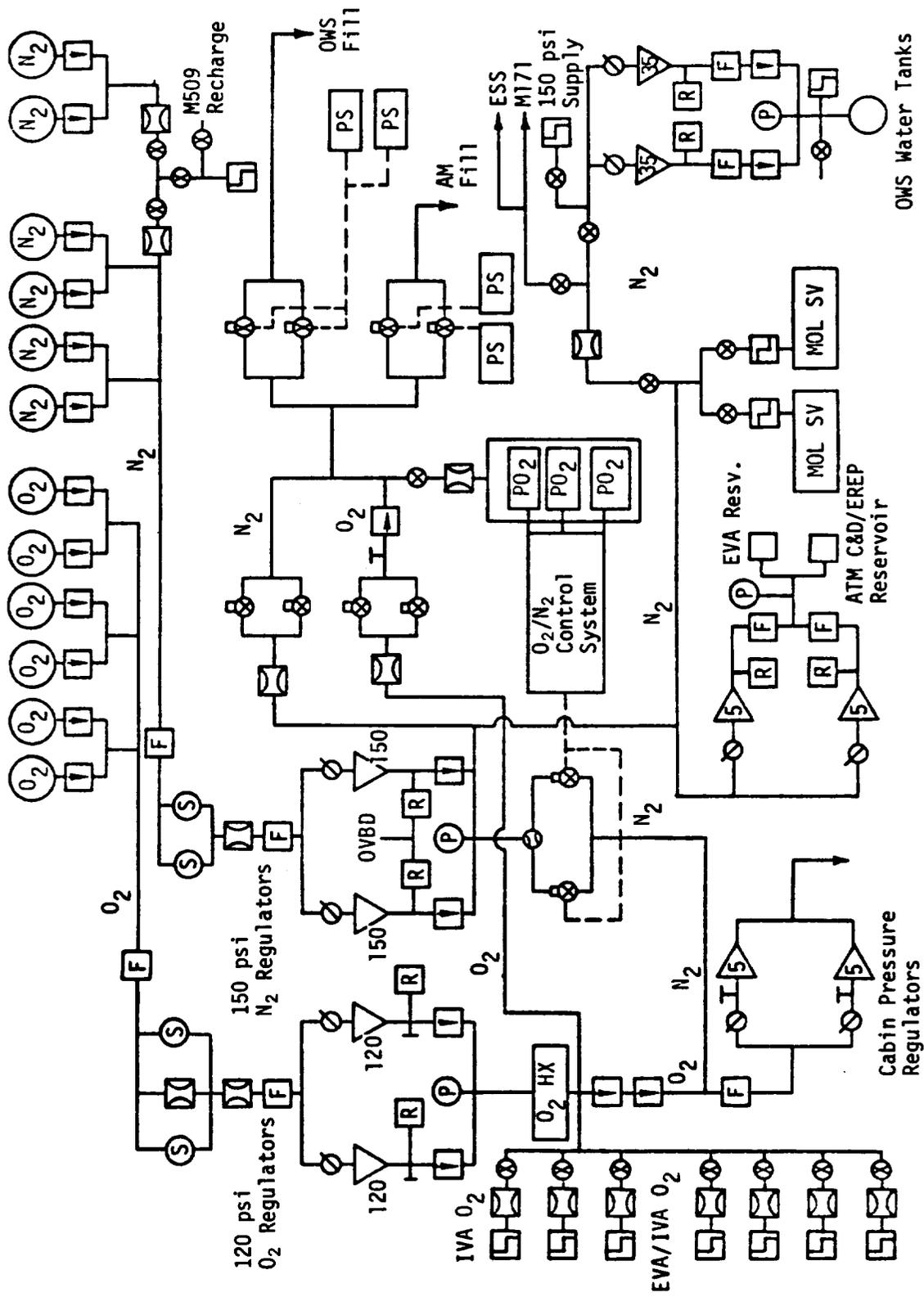


Figure II.M-8 Gas Supply System

the liquid oxygen (LOX) tank. The LOX tank was to be vented through the existing nonpropulsive vent system and a second latching vent valve was added for redundancy.

In the studies preceding the conversion to the DWS concept, the LOX tank (now called the waste tank) was found to be a desirable place to dump numerous types of waste materials. The trash airlock was installed in the common bulkhead and two additional heated dump probes were added for flushing and draining various water systems. Also added were fittings for venting waste processor exhaust gases and refrigeration pump coolant leakage into the waste tank. Because propellants were no longer being carried, it was possible to pre-install all of this hardware.

In the original OWS LOX tank nonpropulsive vent system, flow passed through one port in the tank, two parallel valves and two 20-foot long wraparound ducts to nozzles on opposite sides of the tank. Analytical studies showed that one of the two wraparound ducts would be subjected to temperatures well below the freezing point of water so the duct was likely to become partially or completely blocked, leading to unbalanced thrust. Because this would have placed a large load on the Skylab control system, it was decided to redesign the vent system to its present configuration. The power cost for heating the final 1 ft long duct to prevent freezing was an order of magnitude less than would have been required for the original wraparound ducts. The original waste tank vent system had a small filter screen covering the vent port. Because of concern that this screen would become completely blocked with trash bags, it was replaced by large area screens that separated the waste tank into compartments. The largest compartment received trash bags from the trash airlock. Each vent outlet was in a separate screened-off compartment and these two compartments were connected by a duct made of screen material to assure balanced venting. The liquid dump outlets were separated by screens from the trash area to prevent trash bags from freezing to the dump probes and possibly blocking them.

The original large screens were coarse (16 mesh) because their objective was to control migration of the trash bags. It was later decided to use the screens to prevent overboard venting of any solid waste that might interfere with optical experiments and the 16-mesh screens were replaced with Dutch twill woven screens having 2 micron filtering capability. Extensive developmental tests verified the filtering capability of the new screens but indicated that they could become blocked when urine was dumped on them. A baffle was then added to prevent direct impingement of the dumped urine on the screens. The vent valves on the waste tank were eliminated and replaced by vent caps (once opened, there was no need to close them).

b. Waste Tank Heated Liquid Dump Probe. The original heated probe was 3.5 inches long and extended only 0.5 inch beyond the waste

tank bulkhead. A Kapton heater blanket was wrapped around the 0.25 inch diameter silver tube and held in position with a coil spring. Front and back heaters were sized at 7.5 watts each.

During qualification testing, the heater blanket overheated and failed due to poor thermal contact between the blanket and silver tube. Two attempts to improve the thermal contact (using Eccobond to bond the blanket to the outside diameter of the silver tube and using Nomex yarn woven over the heater blanket to hold the blanket against the silver tube) were unsuccessful.

A decision was made to redesign. The basic objectives were to double the heater power and to increase the heat flux to the probe tip. The length of the probe was increased to extend six inches beyond the bulkhead to reduce ice bridging potential. Redundant heater circuits were maintained and each circuit was positioned lengthwise over the entire length with a watt density of 3 watts/inch at the probe tip and a watt density of 1 watt/inch at the upper end of the probe. The orifice at the tip was angled and located radially to expel liquid parallel to the waste tank baffle, thereby preventing ice buildup.

c. Habitation Area Vent Valve System. The original WWS concept involved fairly elaborate schemes to empty the Liquid Hydrogen (LH₂) tank of all the LH₂ and gaseous H₂, and to increase the temperature from cryogenic H₂ temperatures (-423°F) to 70°F. In addition, H₂ sensors were provided in the cluster to sense the H₂ that would outgas later. The same vent valves used on the Apollo program S-IVB were to be used to vent the LH₂ tank. Workshop pressurization lines and pressure sensing lines had to have burst discs installed in them to prevent cold LH₂ from reaching other parts of the system. After all the LH₂ had been dumped, the discs would be burst and O₂ and N₂ would be used to pressurize the LH₂ tank.

With the change to the DWS concept, the OWS would no longer need to be purged of LH₂ and the burst discs and H₂ sensors were eliminated. Before SL-1 launch, testing indicated the possibility that an excessive delta P across the OWS common bulkhead would occur with the Saturn S-IVB wraparound duct orifice and a vent sequence that allowed the OWS habitation area and waste tank to vent simultaneously at orbital insertion. The initial vent sequence was revised so that the OWS habitation area would be vented at 205 seconds after liftoff rather than at orbital insertion and the orifice diameter decreased from 1.78 to 1.49 inches. These two changes decreased the common bulkhead delta P to acceptable levels.

The OWS pneumatic system for the waste tank and habitation area vent valves was essentially the same as that used on S-IVB except that the regulator was removed. This simplification was the result of a shorter operational life requirement (1 hour versus 7 hours on S-IVB) and confidence in the system's low leakage capability built up during the S-IVB program that permitted lowering the supply pressure to a level within the operational range of the actuators.

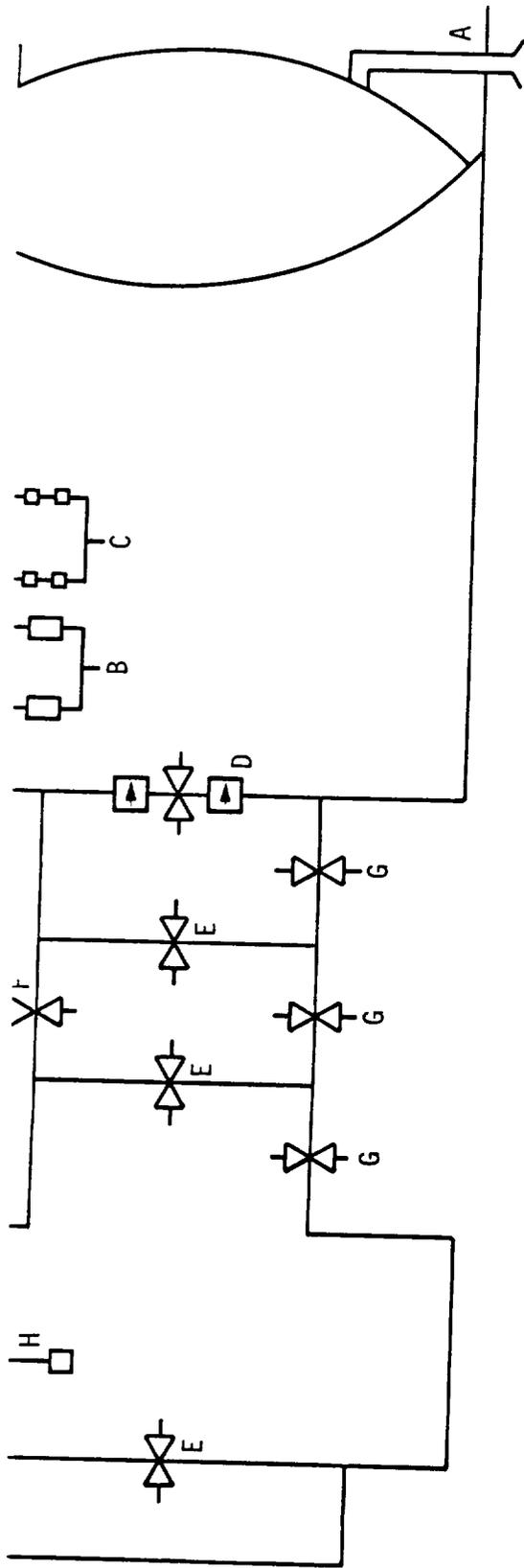
d. Solenoid Vent Valve System. The habitation area vent system on the WWS consisted of the S-IVB pneumatic vent valves and a crew-operated valve for venting the residual hydrogen vapor. At the time of wet-to-dry conversion, it was decided to add capability to vent by ground command at any time in the mission. Because it was believed to be impractical to maintain a pneumatic supply throughout the mission, it was decided to replace the manual valve with a set of four solenoid-operated vent valves. As a result of system design review activities during the SOCAR in 1972, a decision was made to add a vent screen over the entrance to the four solenoid valves to prevent debris from being blown into the valves. Even with the screen, some blockage of the solenoid vent valves occurred during the flight. Without the screen, the effectivity of the solenoid vent valve system would have been severely limited.

e. MDA Vent Valve System. The initial MDA vent valve design consisted of two 4 inch vent valves in parallel. These valves were later installed in series to provide redundancy for the failure mode condition of one valve not closing when commanded by the IU. The originally planned ground command capability for the valves was also deleted because the command capability would be needed only in remote contingency situations.

f. Aft AM Vent-to-Vacuum. This vent was used in the WWS to vent the aft section of the AM to a vacuum during boost, thereby preventing any chance of having a higher pressure in the aft AM than in the OWS while the OWS was being vented to vacuum to remove all the LH₂. The vent could be manually closed by a crewman in the airlock and the aft AM could then be pressurized. When the DWS concept was selected, the valve was removed and two check valves were placed in the OWS hatch to prevent and higher pressure on the aft AM side.

g. Final Configuration. The final configuration of the cluster depressurization systems is shown in Figure II.M-9.

6. Airlock Module Coolant Loop. Several design changes were made to the AM Coolant Loop during the program due to revised system requirements and a few development problems that were encountered. The original concept of the AM coolant loop included a single 40°F thermal control valve downstream of the radiator as shown in Figure II.M-10. The requirement for this configuration was to provide a 55°F water inlet temperature to the Life Support Umbilical interface while absorbing heat loads of 2000 Btu/hour from each of two astronauts. However, a requirement for 45°F water inlet temperatures resulted in moving one of the heat exchangers interfacing the water suit cooling loop with the AM coolant loop upstream of the 40°F control valve. A thermal capacitor was added downstream of the radiator to accommodate the system loads and maintain adequate temperature control throughout the orbital period. A requirement to provide cooling to the ATM console and various EREP components resulted in the addition of the ATM/EREP water cooling loop to interface with the AM coolant loop. The resulting system for the AM coolant loop is shown schematically in Figure II.M-10. The ATM C&D/EREP loop which was added is shown in Figure II.M-11. A major perturbation to this design was produced by a



Legend:

A	Waste Tank Vent	E	Equalization Valves
B	Habitation Area Vent Valves	F	AM Lock Decompression Valve
C	Solenoid Vent Valves	G	AM Cabin Pressure Relief Valves
D	OWS Check & Equalization Valves	H	MDA Vent Valves

Figure II.M-9 Cluster Depressurization System

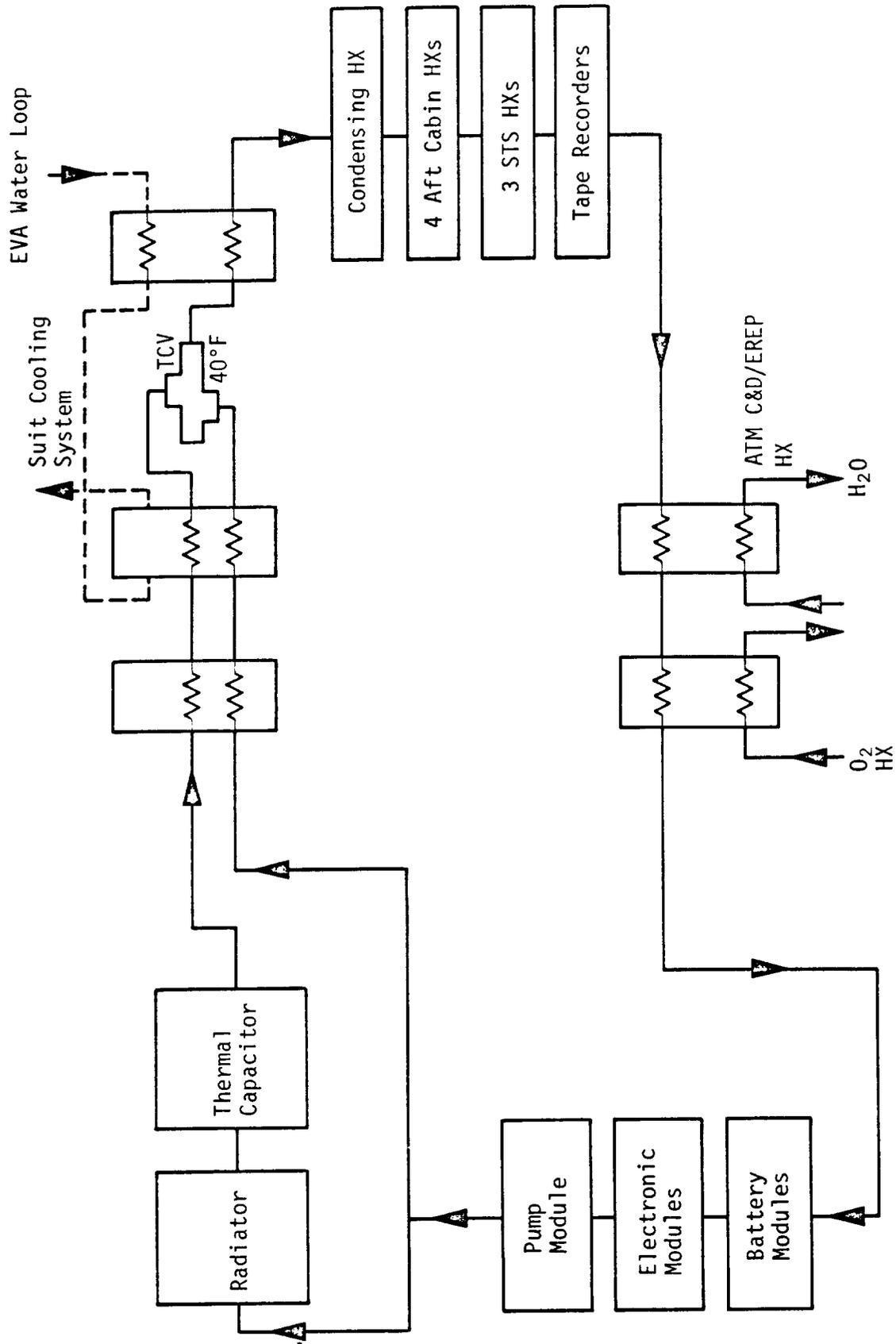


Figure II.M-10 AM Coolant Loop (40°F System)

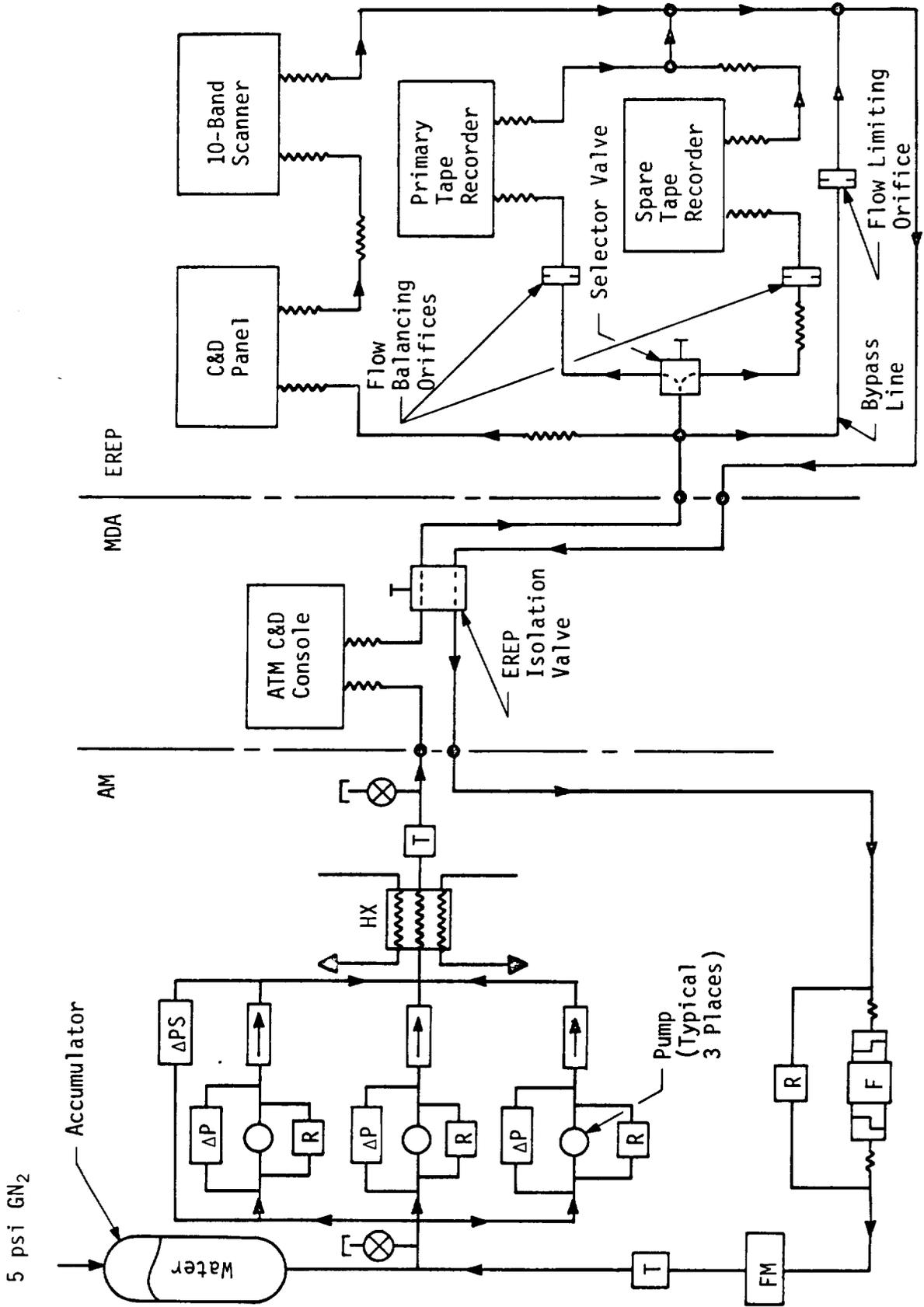


Figure II.M-11 ATM C&D/EREP Water Loop

combination of concerns over the life of the AM batteries with a resulting desire to provide lower battery temperatures and over the inability of the system to maintain cluster dewpoints above the minimum requirement of 46°F. The 40°F control valve at the inlet to the condensing heat exchanger was replaced with a 47°F valve to resolve the dewpoint problem (paragraph II.M.1.b) and the 40°F control valve was relocated upstream of the battery module to provide lower temperatures. A second 47°F control valve was added along with one additional heat exchanger (in each coolant loop) and the system flow paths were rerouted to provide the desired automatic control system. The resulting system is depicted in Figure II.M-12. However, tests conducted to prove the stability of the system showed that the system was unstable.

Because of the short time available to develop a design that would provide control stability, a test approach was taken. The tests led to rearrangement of the lines interconnecting the suit cooling heat exchangers, the addition of a heat exchanger bypass line with bleed orifice, and the addition of the EVA flow selector valve. The final system configuration is depicted in Figure II.M-13. The purpose of the above changes was to thermally isolate the hot and cold inlets to the downstream temperature control valve (TCVB). In the baseline design, the hot and cold inlets were thermally coupled through the heat exchangers upstream of the valve to such an extent that a small temperature differential existed for normal operating conditions and the thermal inertia of the system produced excessive valve movement (and instability) when valve movement was required due to load or temperature changes. Several configurations that incorporated only the rearrangement of lines interconnecting the heat exchangers were tested. Some improvement was seen, but, to attain stability over the required range of heat load and temperature conditions, other changes were necessary. A bypass valve was incorporated for use during non-EVA that completely bypassed the suit cooling system and regenerative heat exchanger. A bleed of approximately 30 lb/hour of cold flow was incorporated that, coupled with the rerouting of lines through the heat exchangers, resulted in stability for EVA conditions.

A design change was required for the thermal capacitor after the OWS Refrigeration System (RS) capacitor failed during qualification testing (The only difference between the AM and RS capacitors was the use of Undecane wax in the RS design rather than Tridecane wax). The container ruptured as a result of forces produced by the volume change during melting. Ullage was available, but the design allowed the ullage to be far removed from the phase change location. In the original design, the cells within the capacitor were interconnected and the ullage could be located anywhere within the capacitor. The final design incorporated a honeycomb cell structure with ullage in each of the cells. Because requirements associated with the Z-LV orientation for expanded EREP operations had significantly reduced the radiator capability for some maneuvers, a second twenty pound capacitor was also added as part of the redesign to provide additional capability.

The original design of the SUS water loop did not incorporate a liquid/gas separator. The separator was added due to concern that free gas might

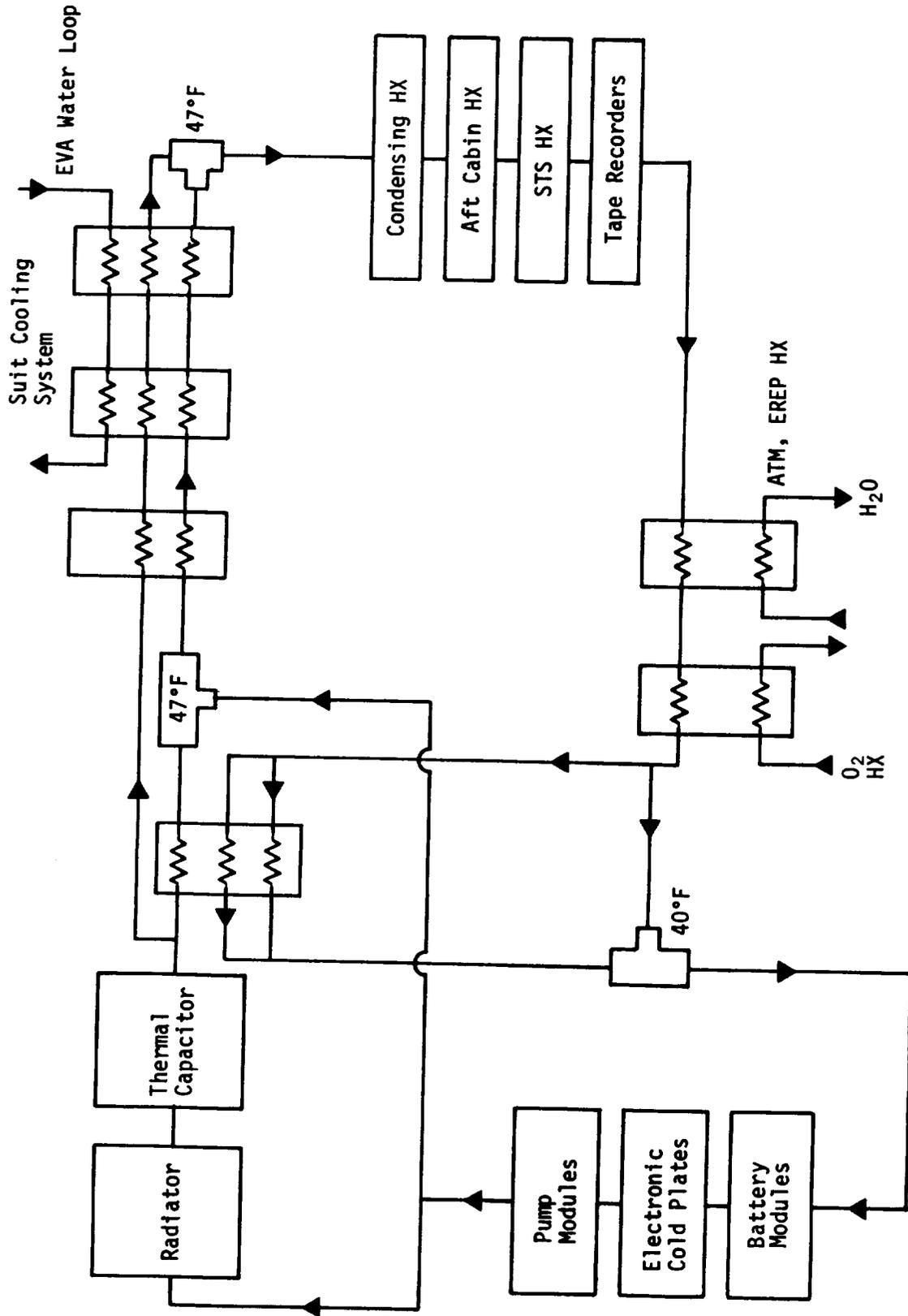


Figure II.M-12 AM Coolant Loop (47° Unstable)

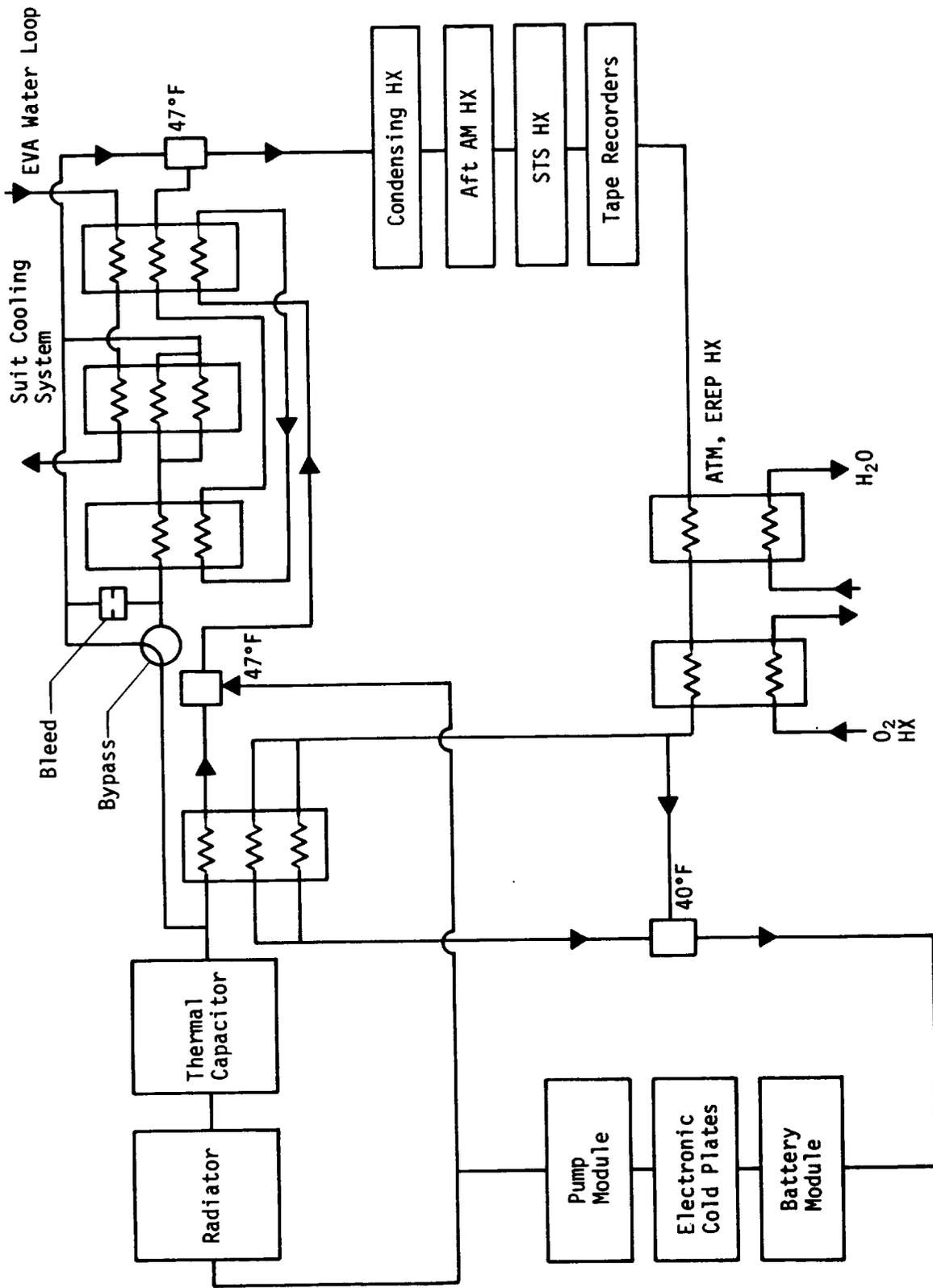


Figure II.M-13 AM Coolant Loop (Final)

be present in the loop. In retrospect, a similar separator should have been added to the ATM C&D/EREP water loop since free gas problems were encountered in flight. However, the Roccal additive in that loop was not compatible with the separator and the approach taken was to minimize the free gas present in the loop. The additives were changed in the SUS loop and the change resulted in additional problems as discussed in the following paragraphs.

Early design of the SUS loops used untreated MMS-606 (deionized) water as the circulating medium. Vendor pump tests using this fluid disclosed starting problems, caused by corrosion on the pump internal parts. These problems forced a change of the pump vanes, rotor, and linear materials from the more wear resistant tungsten carbide to a more corrosion resistant carboloy alloy. The materials changes, combined with the addition of additives to the water for corrosion and bacteria control, resulted in satisfactory pump performance. These additives were 2 percent by weight of dipotassium hydrogen phosphate and 0.2 percent by weight of sodium borate for corrosion control and 500 ppm Roccal for bacteria control. This fluid composition and pump design was also used in the ATM C&D/EREP coolant system.

After installation of the liquid/gas separator in the SUS loops, testing indicated that the Roccal additive was incompatible with the separator performance, causing water carry-over through the gas discharge port. A concern was also expressed about the presence of the Roccal reducing the strength properties of the tygon tubing in the LCGs. The Roccal was therefore replaced by 20 ppm movidyn, another biocide consisting of a colloidal silver solution. Subsequent SUS loop operation with this new fluid resulted again in problems with pump starting. Failure analysis determined that the pump locked up after dormancy due to deposits formed by interaction of the dipotassium hydrogen phosphate and silver in the movidyn with nickel from the fins of the SUS loop heat exchangers. These deposits formed between the pump vanes and rotor interfaces, preventing one or more of the vanes from moving freely in the rotor slots.

At that point in the program, the flight vehicle was undergoing final tests in preparation for shipment to KSC, so a crash effort was undertaken to determine a solution to the problem. The basic approach was to find a suitable replacement for the water solution. Simultaneously, additional design analyses and tests were conducted on alternate pumps and heat exchangers in the event of failure to find a suitable replacement fluid. An alternate pump module, using a modified CSM coolant pump, powered by a transformer and compressor inverter, was designed and tested as a backup to the existing pump module. Also, a design feasibility study was initiated to modify the SUS loop heat exchangers to an all stainless steel configuration.

Neither of the above design changes was required. The final solution was arrived at by beaker-type materials testing and end-to-end systems testing on a variety of candidate fluid compositions. These tests established SUS loop compatibility with a fluid consisting of MMS-606 water

containing additives of 20 ppm molybdenum and 500 ppm sodium chromate. The SUS pumps were also modified by increasing the vane/rotor clearance to further minimize start-up problems.

The flight vehicle SUS loops were drained, cleaned, and reserviced at KSC with the new fluid. The modified increased clearance pumps were also installed. The final system configuration proved to be satisfactory as evidenced by the fact that no problems with SUS pumps were experienced at any time during the mission.

The final configuration of the SUS loops is shown in Figure II.M-14.

7. Refrigeration System. The refrigeration system was added to the OWS when it was changed from the WWS to the DWS configuration. The original RS design included a low temperature proportional mixing thermal control valve similar to the AM cooling loop thermal control valves. This valve controlled the flow through the RS radiator such that the mixed temperature was $-17 \pm 3^{\circ}\text{F}$. The original system is depicted in Figure II.M-15.

Three development problems were encountered with the thermal control valve during development:

- A side displacement (squirring) of an internal metal bellows resulted in drift in the control temperature.
- Outlet temperature instability due to high gain at extremes of sleeve position.
- Poor quality control of bellows welds which resulted in failures during tests.

As a result of the above problems, the valve was deleted from the design. To provide low temperature control of the system, the existing radiator bypass valve control logic was modified. The temperature sense points for valve actuation were moved from the capacitor third segment outlet to the capacitor first segment outlet, and the temperature trip points were adjusted from -20 and -40°F to -13 and -34°F . When -34°F was achieved, the bypass valve was commanded to full radiator bypass. When the sense point warmed to -13°F , the valve returned to full radiator flow. The final system configuration is depicted in Figure II.M-16.

The RS thermal capacitor was redesigned together with the AM coolant loop capacitor as discussed in paragraph II.M.6.

8. Conclusions and Recommendations. Performance of the ECS/TCS systems during the Skylab Missions is reported in TMX 64822, MSFC-Skylab Thermal and Environmental Control System Mission Evaluation Report. The conclusions from that report are provided in the following paragraphs.

The Skylab Environmental and Thermal Control Systems provided an acceptable environment for both crews and experiments. The loss of the meteoroid shield resulted in an imbalance of the passive thermal control

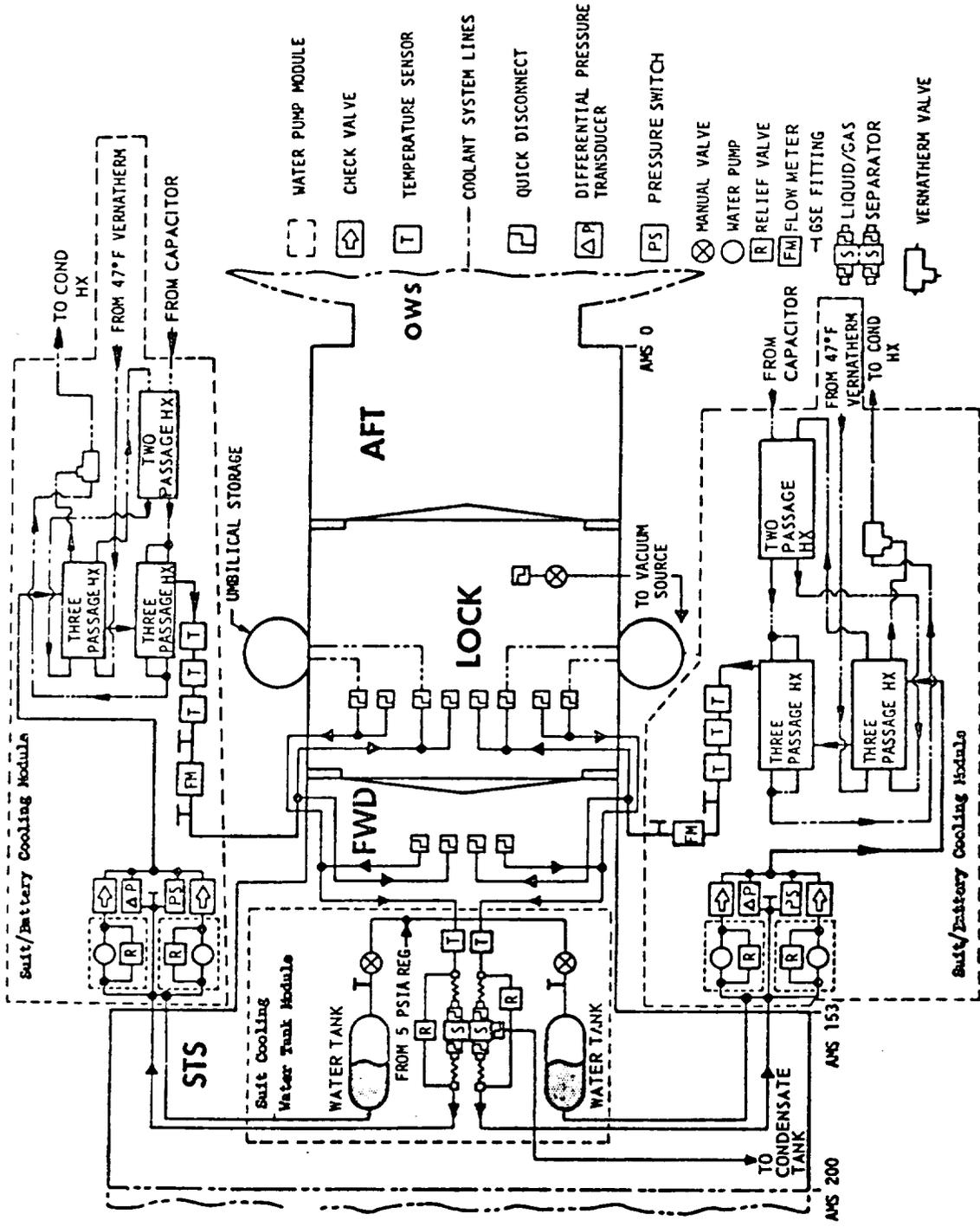


Figure II.M-14 Suit Cooling System

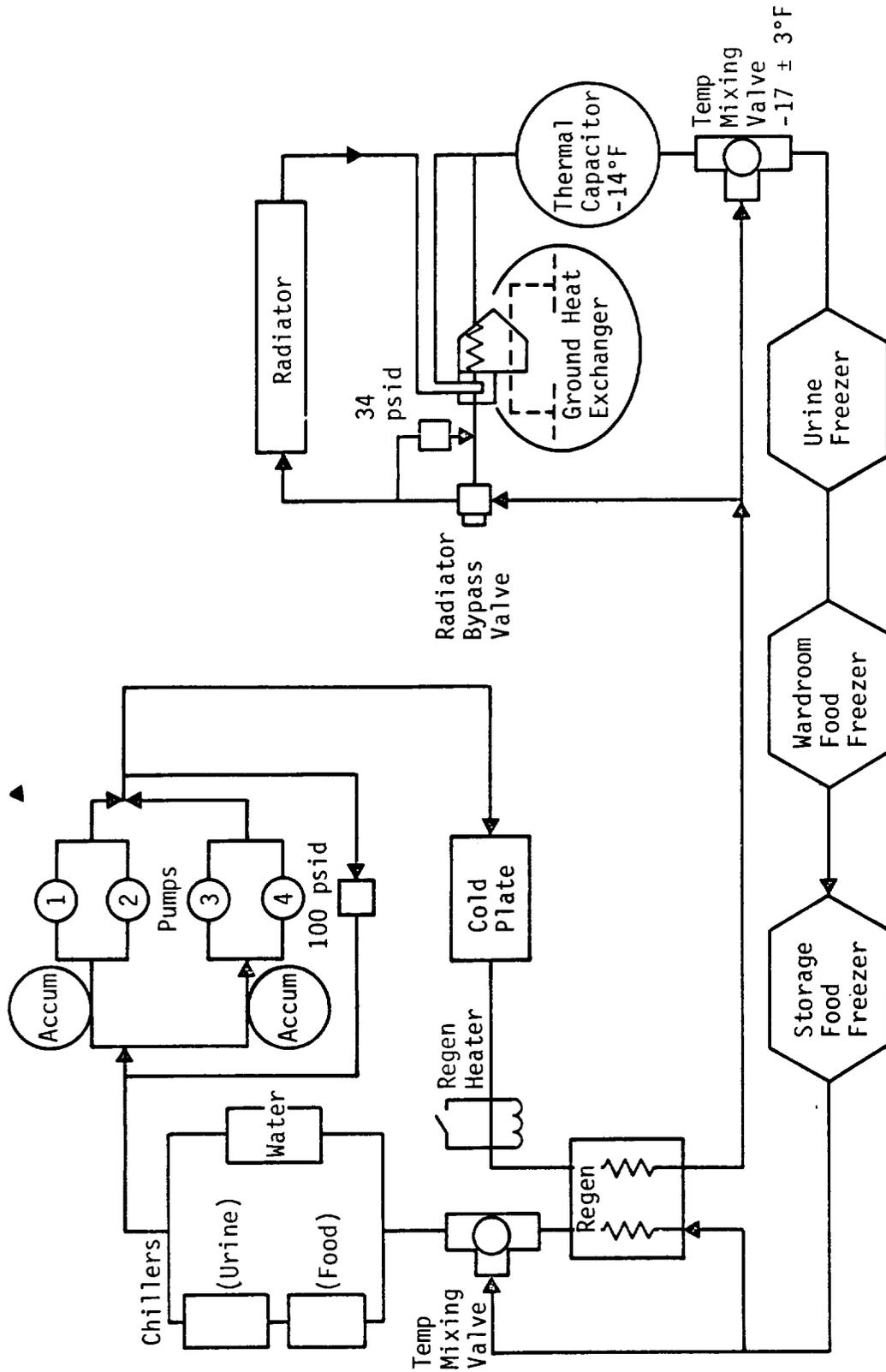


Figure II.M-15 Original RS Design

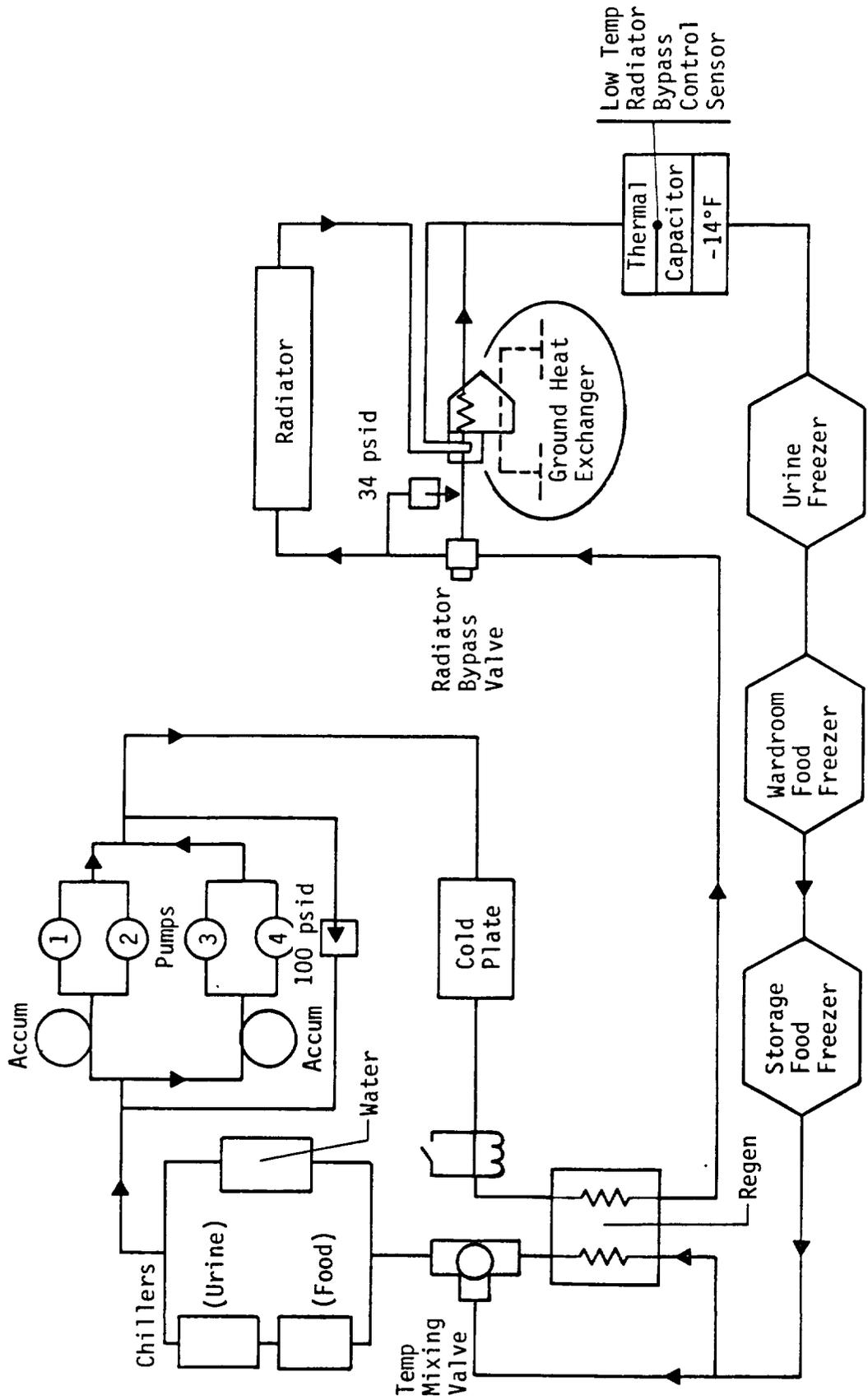


Figure II.M-16 Final RS Design

system for the OWS which was resolved by deploying improvised solar shields. Other anomalies occurred which required coordinated crew and ground support activities in their resolution. The major anomalies, other than loss of the meteoroid shield, were the sticking of temperature control valves in the AM cooling loop, leakage of coolant in both the AM cooling loops and failure of the RS Radiator Bypass Valves (RBPVs).

The following paragraphs provide some conclusions and recommendations for future designs. The comments are grouped by subsystem. A section is also included which contains general comments and observations.

a. Atmosphere Control System. The Atmospheric Control System includes CO₂ removal, humidity control, odor removal, and contamination removal. In general this system performed very well. The crews were basically comfortable and healthy. System discrepancies during the mission were corrected by designed-in system redundancies or by real-time workaroud procedures. Comments and observations relative to future use of similar systems are provided in the following paragraphs.

The condensing heat exchangers using frittered glass water separator plates are an effective, durable and low maintenance means to remove atmospheric moisture.

The performance of the molecular sieve system was outstanding. The system performed CO₂, odor, and moisture removal functions effectively with no system hardware anomalies. In fact, the system performed satisfactorily throughout the 84-day SL-4 mission without a bed bakeout being required (design was 28 days). This system demonstrated that it should be considered for future manned programs, especially those of one month or more duration.

The vacuum side of the condensate system had a tendency for random leaks throughout the mission. The condensate system included many quick disconnects and it was generally agreed that quick disconnect leakage was the problem. The use of quick disconnects should be minimized on future missions in all systems, and especially in vacuum systems. Also braze-type joints are more desirable in vacuum systems than mechanical type joints.

The metabolic guidelines which appear to match the flight data are:

Approximate daily average rate = 440 Btu/hour/man
Metabolic O₂ usage = 1.84 lb/man day
Water production = 2.6 - 4.1 lb/man day
CO₂ production = 2.15 lb/man day

The odor control system performed very well. The crews reported a general lack of odor.

b. Cluster Ventilation System. The Cluster Ventilation System performed well throughout the mission. The crew were comfortable, the gas velocities were acceptable and the equipment used was reliable.

The fans used (modified Apollo PLV types) were adequate. No complaints by the crew of high fan noise levels were made. However, these fans produced a vary low head and any restrictions in the systems caused flow degradation. It is suggested that future missions utilize fans with higher heads so that filter or heat exchanger contamination with lint or moisture will not so seriously effect the cabin gas flow.

Lint is added to the atmosphere on long duration flights in quantities sufficient to collect on cabin heat exchanges and cause a reduced gas flow. The susceptibility of fan/heat exchanger units contamination should be an important consideration in the choice of equipment for future ventilation systems. Future use of these type components should include finer mesh protective screens, and increased accessibility for periodic replacement and cleaning.

Much improvement in the design and installation of cabin gas flow meters is needed. The heat pulse type flow meters used in the AM systems consistantly fluctuated through 15-20 percent of the full scale flow. Single data points were of little meaning and long term averaging afforded the only means of determining the flow rate. The vane type flow meters in the OWS ducts were not satisfactory either since two of the three units failed.

c. OWS/MDA/AM Thermal Control System. The OWS/MDA/AM Thermal Control System, outside of the loss of the meteoroid shield, performed within the specified limits. As shown in TMX-64822, the cluster temperatures stayed within the comfort box except prior to parasol deployment and during high beta angle periods. A one-to-one comparison of flight versus design is not possible due to the loss of the meteoroid shield, but enough data are available to show that the design was adequate.

A considerable number of telemetry sensors had been installed in the OWS for TCS system evaluation. These proved to be very valuable and even more would have been useful in predicting the maximum temperatures when the meteoroid shield anomaly occurred.

When the OWS was hot and the MDA was cold, it would have been desirable to have a flexible cloth duct which could attach to a portable fan and direct the flow from one compartment to the other. This would require very little storage volume or weight and would add a considerable amount of flexibility should a similar anomaly occur in future programs.

The crew comfort criteria appears to be a good criteria as the crew tended to turn the thermostat up or down when approaching the upper and lower limits of the comfort box. Radiation heat from hot walls was very noticeable. Jackets and gloves were worn on initial entry into the OWS to help shield against the heat from the walls.

d. Gas Supply System. The Cluster Gas Supply System performed well and demonstrated that the design concept as well as most of the components should be considered for future flights. With the exception of

the 150 psig N₂ regulator pressure, which drifted low, (but still within useful range), the gas system was problem free.

The two-gas control system was especially effective in providing cabin pressures and O₂ partial pressures well within the allowable range. A two-gas system most probably will be used on all future, long-term manned space flights and this type of control is suggested as a candidate.

Cluster O₂ and N₂ gas usage rates were well below design levels; significant quantities of both gases were available at the end of the mission even though unplanned purge cycles were accomplished and cabin pressures were maintained at near manned level during the orbital storage period following SL-3. The total vehicle pressure integrity design was therefore very effective and should be considered in the future.

Even though no damage resulted, the fact that the O₂ bottle number 6 went above design/qualification limits four different times during the mission demonstrates the need for thermovacuum test to backup analyses. If the tank had been marginally designed, catastrophic consequences could have resulted. A thermovacuum test would probably have revealed this analysis error.

To help evaluate system performance and metabolic rates and determine cluster leakage rates, flow rate measurements on gas flow during pressurization, EVA/IVA and normal cabin pressure regulator flow would have been useful.

c. Pressurization/Depressurization Systems. The Pressurization and Depressurization Systems performed nearly as predicted. All valves were adequately sized for the volumes to be depressurized.

The ice buildup on the AM depressurization valve screen during depressurization indicates that attention should be given to this problem in the future. By having a removable outer screen, such as the one used for SL-3 and SL-4, the hazard of allowing chips of ice to possibly damage the valve seat is eliminated, but the vent procedure is slightly larger and more complicated. Heaters should be considered in future designs.

An accessible screen was added to the inlet of the solenoid vent port as a result of a preflight design review. The crew was required to clean the screen on several occasions and had the screen not been present, the vent valve could have been blocked. Screens should be provided for similar future designs.

Cluster structural leakage was approximately 20 percent of maximum allowable specification leakage.

f. Airlock Module Coolant Loop. The AM coolant loops, from a performance standpoint were well designed. The electronics were properly cooled, the crew was maintained comfortable during EVA, and

in general the heat rejection capabilities were more than adequate. However, these systems experienced some mechanical failures which, although they were resolved or worked around, demonstrated a need for higher reliability. The radiator/thermal capacitor performance was good.

When one of the AM coolant loop temperature control valves stuck, the other, completely separate, loop experienced the same failure at the same time. This has been attributed to contamination originating in heat exchangers which were identified and processed alike, jamming valves which were alike and processed alike. This failure was similarly repeated in the OWS refrigeration system, where two completely separate and redundant systems experienced the same problem at the same time. Also, although the locations are not known, both AM coolant loops leaked and neither OWS refrigeration systems leaked. These failures indicate that systems containing the same generic components do not provide the degree of redundancy obtainable in systems with different generic parts. Although the latter case is obviously more expensive it definitely has merit, especially where mission or life critical systems are concerned.

Also, systems should be designed to allow inflight reserVICing with ease and extra fluids should be stowed whenever possible. If Skylab had been one long continuous flight, the AM coolant systems would have been lost, terminating the mission early. The number of mechanical fasteners in fluids systems should be minimized.

Consideration should be given to ultrasonic cleaning of heat exchangers and other components in systems with contamination sensitive elements.

The EVA/IVA system performed well enough to include some lengthy and strenuous workshop repair tasks, resulting in expansion of original mission objectives. All mission objectives were accomplished and at no time was crew safety compromised. It is recommended that the Airlock EVA/IVA system - design concept, verification procedure, and operational hardware - be considered on future missions with an EVA requirement.

Some design requirements were inconsistent with Skylab EVA experience.

- Waste heat load range requirements of -800 to +2000 Btu/hour man was too severe. Maximum heat load for all three crewmen was approximately 2200 Btu/hour and a negative heat load was not experienced.
- The maximum allowable water delivery temperature of 50°F was too severe. Temperatures of 58°F provided adequate cooling.
- Total duration of EVA exceeded seven hours, with cooling water flow exceeding eight hours - system requirements were three and four hours, respectively.
- The system was designed to support two EVA crewmen on one loop with the other crewman (STS) on second loop. During the mission, a single loop effectively supported all three crewmen.

Oxygen flow and suit cooling system support was provided as required for 12 EVA/IVA operations including, on DOY 359, a record EVA hatch open time exceeding seven hours.

Loss of SUS number 1 cooling fluid occurred due to leakage of LCG/PCU during an EVA. Reservice, as planned and provided for, was accomplished. Provisions to allow inflight reservicing of fluid systems should be included in all future missions.

Differential pressure instrumentation was deactivated prior to launch due to a potential of shorting out the 5 volt bus and eliminating all instrumentation connected to that bus. Loss of delta P information complicated the determination of loop performance and the isolation of flow problems.

The ATM C&D/EREP cooling system flow became erratic late in the SL-3 mission. Successful deaeration of the loop, using the liquid gas separator, temporarily corrected the flow oscillations. Deaeration devices should be included in future systems where any point in the system operates at pressures below cabin or ambient pressures.

g. Refrigeration System. The RS was used to thermally control the frozen food and urine samples, the refrigerator and water chiller and the chilled urine sample pool. The RS performed very well during the mission with the exception of the anomaly which occurred on DOY 173.

In fact, the system was able to maintain the specified requirements even during the abnormally hot internal conditions before the parasol Sun shield was deployed.

The only serious anomaly to occur in the RS was the failure of both the primary and secondary RBPVs on DOY 173. The failure was attributed to contamination, which prevented the bypass poppet assembly of both valves from fully seating or opening, although the radiator port poppets in each valve were only prevented from seating. The primary RBPV performance was improved by cycling the valve from the ground by enabling and disabling the loop. The improvement was such that the system was able to essentially maintain its requirements for the rest of the mission. As mentioned in the Airlock Module Coolant Loop section (paragraph II.M.8.f), the same generic components in dual loops did not give the required degree of redundancy. Further, cleaning and filtration requirements must be closely scrutinized relative to the particulate contamination size which causes valve or component failure.

After the initial low performance of the RS radiator following orbital insertion, the radiator performed as predicted throughout the remaining missions. The absorbed heat flux on the radiator was nominal and there was no apparent degradation of the radiator paint (most of the white paint on other external areas of Skylab showed significant degradation as a result of solar exposure and/or retrorocket plume contamination).

Thermal capacitor performance following umbilical disconnect at SL-1 launch until radiator activation was as anticipated. Comparison of thermal capacitor data at various times throughout the mission revealed no degradation in performance that would have been caused by wax leakage.

Flight data revealed no evidence of either pump degradation or coolant leakage in either of the two RS coolant loops.

All RS internal loop segment components performed as expected including the Chiller Thermal Control Valve (CTCV) and regenerative Hx. At no time did flight data indicate the regenerative heater in either of the two coolant loops to have been activated to aid in the regenerative capability of the regenerative Hx.

Crew Complaints with the RS consisted of:

- Inconvenience of the inner door on the freezer compartments.
- Poor space utilization in the freezers.
- Lack of canister restraint in the food chiller.
- Ice buildup on the surface between the freezer compartment doors impaired the latching of the freezer doors to such an extent that periodic cleaning became necessary.

h. Ground Thermal and Fluid Conditioning Systems. The Ground Cooling Systems provided sufficient cooling to freeze the airlock thermal capacitors ($\approx 10^{\circ}\text{F}$). This method of using a heat exchanger to transfer waste heat to a ground system prior to liftoff and a phase change material to supply heat removal en-route to orbit seems to be a sound method and should be considered in the future.

Both the refrigeration ground conditioning system and the OWS ground TCS performed as anticipated. No anomalies occurred in either of these two systems.

i. General Comments. Both the AM coolant loop and the OWS RS demonstrated that when the control valves were stuck in a near optimum position, the outlet temperature would be acceptable without automatic control. This would suggest that for a reliable long life system with the man available, a backup hand valve may be desirable in parallel to the automatic system should it be required.

The nominal standard solar constant of $429.2^{+14.6}_{-14.0}$ Btu/hour-ft² which allows for seasonal variation appears to match the Skylab flight data. The Earth albedo and emitted radiation values versus latitude and the seasons standard also appear to match the Skylab flight data. In retrospect, the $\pm 3\sigma$ and $\pm 2\sigma$ environmental flux values which were used for design purposes were probably conservative but should

still be used in future programs to offset degradation in coatings, actual conductances, actual heat loads, active system performance variations and anomalies.

The Z-93 radiator coating when continuously exposed to the Sun as it was in the D024 experiment, can degrade from the as launched value of $\alpha/\epsilon = .14/.91$ to approximately $.34/.91$ in 123 equivalent Sun days. If only one side of a cylinder is exposed as on the AM radiator, the degradation averaged around the cylinder would be approximately $.25/.91$.

All critical systems in a manned vehicle should have adequate TM, DCS command capabilities, and manual overrides as used in Skylab. This combination was invaluable in troubleshooting the problems and in providing system workarounds.

All systems with compatible fluids should have facilities to use each others fluids, (i.e., O_2/N_2 could have been used for TACS, AM coolant could have been refilled by OWS RS).

Critical components should be accessible, and adjustable, (i.e., AM coolant control valves, OWS refrigeration control valves, etc). All automatic controls should have manual overrides whenever possible.

Detailed review/test of tolerances, filters, and cleaning should be performed. Performance tolerance should be as loose as possible to allow increased physical tolerances in components.

Simple inflight calibration of sensors is desirable wherever possible.

When real-time system analysis is required, sensors should be provided for all possible measureable parameters. Although it is classically hard to support a need for these sensors preflight, the Skylab flight demonstrated the value of adequate system instrumentation.

N. Logistics

1. Logistics Planning and Implementation. The logistics support program for Skylab payload equipment under the design cognizance of MSFC was conducted in accordance with NASA Headquarters, Skylab Program Center, and Skylab Project level logistics plans and requirements documents. These plans are depicted in Figure II.N-1.

The Apollo Applications Logistics Requirements Document, NHB 7500.3, published by the Office of Manned Space Flight, identified the logistics requirements for the Skylab Program. This document delineated the objectives, planning, responsibilities, and requirements in the major logistics functional areas necessary to identify, integrate, and implement Skylab logistics requirements. The requirements of this document were applicable to all Skylab Center Managers and were implemented by all Manned Space Flight organizations participating in the Skylab Program. These requirements pertained to all Skylab hardware end items, experiments, and ground support equipment.

The basic Skylab logistics objectives were to:

- Ensure the timely availability of required material and services;
- Maximize use of existing material, systems, facilities and services;
- Procure only that additional material, systems, and services necessary to support Skylab requirements;

The Skylab Program Payload Logistics Plan, MM7500.6, was prepared and maintained by the MSFC Logistics Manager, PM-SL-GS. This plan established the guidelines for the objectives, concepts, responsibilities, and general requirements for accomplishing the MSFC payload logistics functions for the Skylab Program. General concepts, objectives, and policies contained in the OMSF Apollo Applications Requirements Document NHB7500.3, and applicable portions of the Logistics Requirements Plan for MSFC Programs, MM7500.2, were reflected in the plan. In addition to defining the minimum functions and logistics tasks required of the Skylab Program Office, Projects Offices, Science and Engineering organizations, and contractors to implement their logistics programs, the plan also directed accomplishment and documentation of the planning and analyses required to satisfy logistics requirements, and established the framework within which the resulting logistics products were scheduled, statused, and made available to support program activities.

Logistics planning included the support required during postmanufacturing checkout, integration and test at MSFC, tests at locations other than MSFC, and prelaunch and countdown operations at KSC, and was applicable to the following logistics elements:

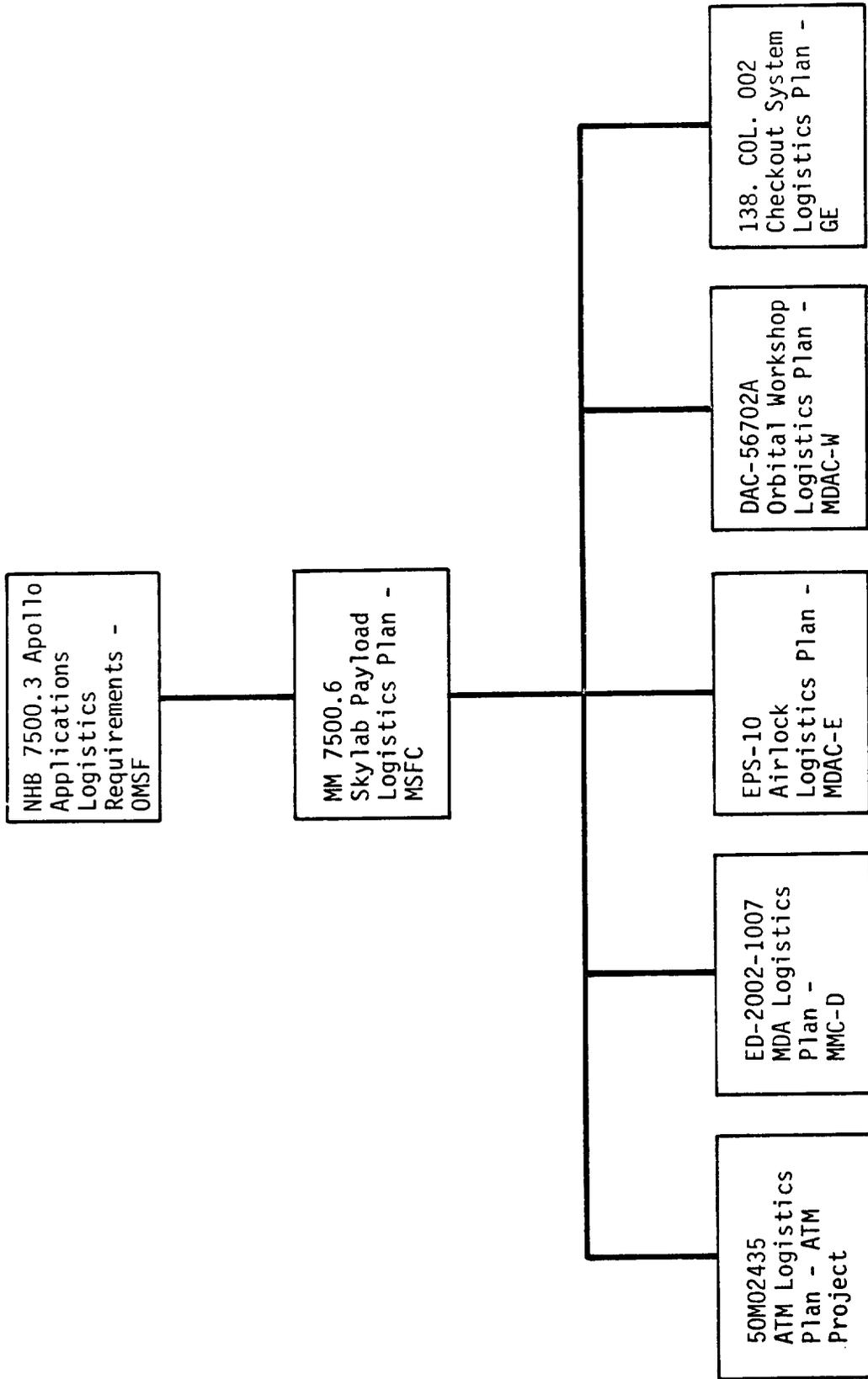


Figure II.N-1 Skylab Payload Logistics Planning

- Maintainability,
- Maintenance Requirements,
- Spare Parts and Supply Support,
- Propellants, Pressurants and Ordnance,
- Base Services and Facilities,
- Logistics Personnel Training,
- Maintenance Instructions,
- Transportation, including Preservation, Packaging, Packing, Marking, Handling and Shipping,
- Configuration Control of Logistics Products,
- Inflight Maintenance.

Because of economic limitations and logistics constraints imposed by one-of-a-kind systems and experiments, standardization of methods was not a prime consideration in developing program level integrated logistics planning. In order to obtain maximum support at minimum cost, emphasis was placed on use of existing methods, resources, and available assets. By not specifying precise documentation formats and by relaxing some of the more stringent requirements normally required for MSFC programs, the contractors and organizations within MSFC responsible for providing logistics support were able to simplify their support programs. This concept not only proved successful from a support standpoint, but because major contractors were permitted to use existing or simplified systems and methods, it proved successful from a cost standpoint.

The Skylab Program Logistics Plan was supplemented by individual project level logistics plans, which were developed to amplify the implementation of the logistics programs and identify project peculiar support concepts, policies, and objectives. The project plans covered performance of analysis to establish support requirements, implementation, and furnishing of logistics support and methods for accomplishing these tasks. Where required by KSC contract, additional project level plans were prepared to describe the functions and methods associated with maintenance, spare inventory management, replenishment, replenishment of spares and sustaining functions performed at KSC.

Logistics support provided for experiments varied. In some cases, complete logistics support was provided; in other cases, support was limited. Due to austere funding and the one-of-a-kind concept, there were no individual experiment logistics plans. The extent of support provided was based on the maintenance concept and contractual require-

ments placed on experiment developers by the development centers. In-flight Maintenance planning and support is discussed in Chapter L of this report.

2. Support Concepts and Objectives. The prime objective of the maintainability program was to ensure that the hardware design incorporated features that minimized and facilitated maintenance, and minimized costs and problems associated with maintenance and logistics support.

The maintenance concept for the flight and backup modules and ATM was to perform first level maintenance, normally component (black box) replacement directly on system installed equipment, at the integration and test locations. Second and third level maintenance was normally accomplished at the supplier's facility. The same concept applied to GSE, except that some second level maintenance was accomplished at the field sites. Assignment of responsibility to major end item contractors for performance of scheduled and unscheduled maintenance contributed to the success of the maintenance program and resulted in the reduction, and, in some cases, deletion of maintenance procedures, since this effort was accomplished by contractor trained and certified personnel. The basic concept for maintenance of experiments was to remove the flight article and replace it with the backup article. This concept was modified whenever it was more feasible and economical to accomplish in-place repair and the necessary maintenance requirements were available. Instructions for maintenance of experiments were provided by the experiment developer or development center. These instructions were in the form of operation, maintenance, and handling procedures, or they were included in other experiment documents. Instructions for maintenance of the Skylab modules, ATM and associated ground support equipment, where required, were furnished in various forms using existing systems and methods. Maintenance documentation furnished by the major suppliers, along with spares and transportation documentation, are depicted in Figure II.N-2.

The program and mission time constraints and the fact that the items being supported were one-of-a-kind and of short operational use, dictated that spare parts supplied in support of maintenance be of assembly or subsystem level rather than piece-part-type items. Spare parts required for repair of removed items were kept to a minimum and, in most cases, held at the supplier's facility. Spares quantity determinations were based on anticipated usage, issuance, operating times, lead times, repair time, costs, system down times, allocations, and program schedules. Another factor affecting the selection and provisioning of spares was the availability of the backup articles. The initial spares philosophy called for provisioning of only the flight articles and associated equipment with the backup articles available for cannibalization in a contingency or emergency situation. This philosophy permitted the contractors and other organizations responsible for providing spares, to provision minimum quantities, and eliminated the need for provisioning of high-cost/low-probability of failure type items. Deviations to this philosophy were made when the capability to launch

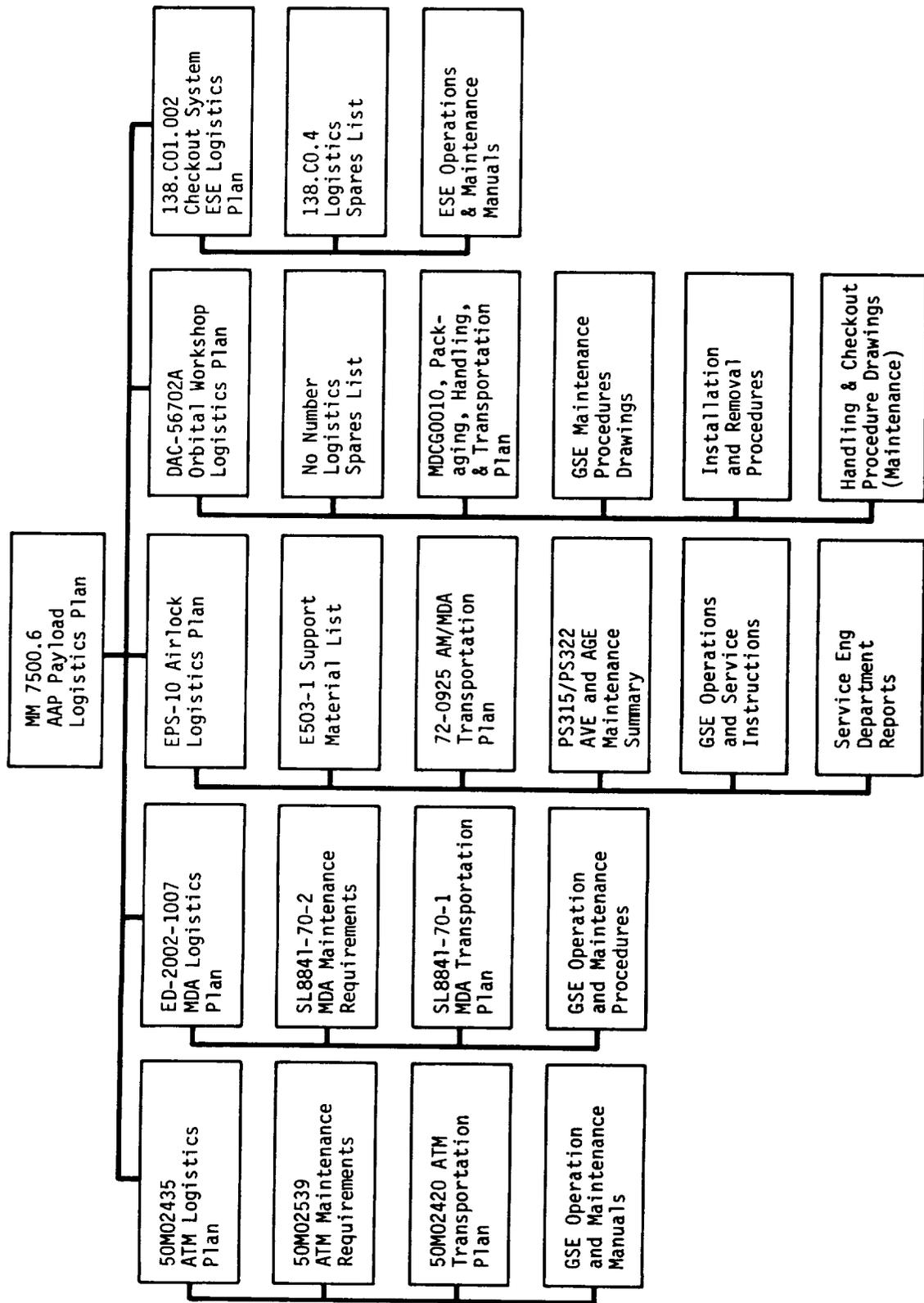


Figure II.N-2 MSFC Module and ESE Logistics Documentation

the backup article was imposed by the Payload Backup ten-month turn-around program. Instead of supporting just the flight article from logistics spares and components from the backup article, spares were required to support both articles during the same period at two different locations. This resulted in the procurement of those items not previously provisioned by the major suppliers and the reprovisioning of those items where additional quantities were required to support the added usage.

Spares inventories were initially established at the major end item supplier's facility for support of test and checkout activities at the respective locations. These inventories consisted primarily of those items that could be readily replaced by first level maintenance on system installed equipment. From these inventories, spares were allocated to other test locations or shipped on an individual basis to the test site as required. Inventories were established at KSC by all major contractors along with appropriate inventory control and management procedures. Custody of the spares inventories remained with the contractors throughout the program. This permitted the movement of spare items with a minimum of formality and accelerated the turnaround of items for repair or modification.

In the interest of avoiding costs associated with identification and segregating logistics spares into an additional category as required for surveillance of Launch Critical Spares, no launch critical category was established. However, spares shortages and the program impact of shortages along with appropriate workaround methods were reported at Launch and Flight Readiness Reviews.

Transportation of Skylab Payload modules and ATM was accomplished in accordance with the suppliers transportation plans and procedures. Transportation planning encompassed movement sequence, transportation mode and route, GSE required, environmental and contamination control, loading and off-loading, and preparation for receipt and inspection. The basic objective was to ensure equipment was transported by the most economical and practical means that would ensure its arrival at the proper location at the designated time free of damage. Figure II.N-2 identifies the special transportation planning developed by the major suppliers for the flight articles. Additional plans were prepared for the backup, trainer, prototypes, etc., where required. Transportation of experiments, when transported separately, was accomplished with instructions provided in Operations, Maintenance, and Handling Procedures and other data provided by the experiment developer.

3. Logistics Management and Status. The Skylab Program Office within MSFC Program Management Directorate was responsible for management of the Skylab logistics effort. This responsibility was administered by the Skylab Logistics Manager who reviewed and approved logistics planning, monitored logistics program activities to ensure a consolidated logistics program, and coordinated inter- and intra-Center logistics activity.

Logistics management status visibility was maintained through constant contact with the project offices, module contractors, experiment offices and suppliers by visits, telephone briefings, meetings, and formal and informal correspondence. A complete summary of the logistics requirements for Skylab Payload equipment, including experiments, was maintained to enable logistics management personnel to review, monitor and evaluate the current logistics support posture. Transportation and appropriate procedures of program critical hardware was closely coordinated and monitored to preclude in-transit damage and ensure prompt delivery. Funding and scheduling of all special transportation (NASA Barge, Point Barrow, and Guppy Aircraft) for Skylab outsized cargo was provided by the logistics management office.

4. Conclusions and Recommendations. The Skylab Logistics Program provided support of the test, checkout, and launch activities without schedule impact, and a major objective of using available systems and resources where possible was satisfactorily attained.

Future logistics support programs could be managed more effectively if support contracts contained provisions for reporting logistics status. This would be especially advantageous when logistics data was nondeliverable, which was the case with some Skylab contracts.

Inflight maintenance planning was not considered to be a logistics function for the MSFC Skylab program. Planning for inflight maintenance was not started during the advanced studies, definition, or design/final definition phases, but during the development/operations phase, which was too late to incorporate design features that would have expanded inflight maintenance capability.

It is recommended that inflight maintenance planning of future MSFC manned flight programs be initiated during the advanced studies phase of the program, and be conducted as part of the overall logistics planning activities.

0. Experiment Development and Integration

The evolution of the Skylab Program and corollary experiment payload development and integration are described in the "MSFC Skylab Corollary Experiments Final Technical Report," NASA TM X-64809. The procedures employed by MSFC and contributing contractors to bring these experiments from their initial selection through launch and mission support are discussed. The MSFC had development responsibility for 59 experiments and integration responsibility for 88 of 94 total program experiments of which 60 were treated as corollary experiments.

The experiment payload selection was guided by the program objectives, which were (in order of priority):(1) biomedical and behavioral performance, (2) man-machine relationships, (3) long-duration systems operations, and (4) experiments (solar astronomy, scientific, engineering, technology, and other corollary experiments). The final complement of experiments was also influenced by major NASA decisions to employ the cluster concept and the DWS, and to incorporate Earth Resources experiments. Three groups of experiments were added in the two years before launch. These included additional materials processing experiments, student experiments, and space environment experiments. Finally, two investigations were conceived and added during the mission: the Comet Kohoutek viewing program, and the science demonstrations. The Skylab flight experiments are identified in Table II.0-1.

1. Design Evolution. The initiation of an experiment varied, but basically the PI submitted a proposal to one of the Sponsoring Program Offices (SPOs), or responded to an Announcement of Flight Opportunities (AFO) prepared by one of the SPOs. The proposal was presented by the SPO to the Manned Space Flight Experiments Board (MSFEB), which recommended to the Skylab Program Director that it be considered for assignment to the Skylab Program. Experiments approved for consideration were assigned an Experiment Development Center (EDC) and Experiment Integration Center (EIC). The EDC role was assigned to the appropriate NASA center, depending on the nature of the experiment. The MSFC or JSC acted as proxy Development Center (see Table II.0-1) for some Skylab experiments developed by other NASA centers or Government agencies that had not established major Skylab organizations. The EIC was usually MSFC, unless the experiment was planned to be operated entirely in the CSM, in which case it was JSC. The EIC functions for the MSFC Skylab Program Office were performed by the Experiment Development and Payload Evaluation Project Office (SL-DP), with the exception that ATM experiments were integrated by the ATM Project Office (SL-SE-ATM).

An Experiment Implementation Plan (EIP) was prepared by the EDC, with support from the PI, and coordinated with the EIC, the Launch Operations Center at KSC and the Mission Operations Center at JSC. The EIP contained an experiment summary, experiment description information, and sections on the development approach, integration approach, and programmatic information. The experiment descriptive information was

Table II.0-1. Skylab Flight Experiments/Instrument

NUMBER	EXPERIMENT TITLE	DEVELOPMENT RESPONSIBILITY		INTEGRATION RESPONSIBILITY		COROLLARY EXPERIMENT
		MSFC	JSC	MSFC	JSC	
D008	Radiation in Spacecraft	X(DOD)	X(DOD)			X
D024	Thermal Control Coatings	X		X		X
ED11	Absorption of Radiant Heat in Earths Atmosphere	X		X		X
ED12	Space Observation and Prediction of Volcanic Eruptions	X		X		X
ED21	Photography of Libration Clouds	X		X		X
ED22	Possible Confirmation of Objects within Mercury's Orbit	X		X		X
ED23	Spectrography of Selected Quasars	X		X		X
ED24	X-Ray Content in Association with Stellar Spectral Classes	X		X		X
ED25	X-Ray Emissions from the Planet Jupiter	X		X		X
ED26	A Search for Pulsars in Ultraviolet Wavelengths	X		X		X
ED31	Bacteria and Spores	X		X		X
ED32	In Vitro Immunology	X		X		X
ED41	Motor Sensory Performance	X		X		X
ED52	Web Formation	X		X		X
ED61	Plant Growth	X		X		X
ED62	Plant Phototropism	X		X		X
ED63	Cytoplasmic Streaming	X		X		X
ED72	Capillary Studies	X		X		X
ED74	Mass Measurement	X		X		X
ED76	Neutron Analysis	X		X		X
ED78	Liquid Motion	X		X		X
H α -1	ATM Hydrogen Alpha Telescope No. 1	X		X		X
H α -2	ATM Hydrogen Alpha Telescope No. 2	X		X		X
M071	Mineral Balance					
M073	Bioassay of Body Fluids		X			X
M074	Specimen Mass Measurement		X			X

Table II.0-1. (continued)

NUMBER	EXPERIMENT TITLE	DEVELOPMENT RESPONSIBILITY		INTEGRATION RESPONSIBILITY		COROLLARY EXPERIMENT
		MSFC	JSC	MSFC	JSC	
M092	Inflight Lower Body Negative Pressure		X	X		
M093	Vectorcardiogram		X	X		
M112	Man's Immunity, In Vitro Aspects		X	X		
M113	Blood Volume and Red Cell Life Span		X	X		
M114	Red Blood Cell Metabolism		X	X		
M115	Special Hematologic Effects		X	X		
M131	Human Vestibular Function		X	X		
M133	Sleep Monitoring		X	X		
M151	Time and Motion Study		X	X		
M171	Metabolic Activity		X	X		
M172	Body Mass Measurement		X	X		
M415	Thermal Control Coatings	X		X		X
M479	Zero Gravity Flammability	X		X		X
M487	Habitability/Crew Quarters	X		X		X
M509	Astronaut Maneuvering Equipment		X	X		X
M512	Materials Processing Facility		X	X		X
M516	Crew Activities and Maintenance Study		X	X		X
M518	Multipurpose Electric Furnace System		X	X		X
M551	Metals Melting		X	X		X
M552	Exothermic Brazing		X	X		X
M553	Sphere Forming		X	X		X
M555	GaAs Crystal Growth		X	X		X
M556	Vapor Growth of IV-VI Compounds		X	X		X
M557	Immiscible Alloy Composition		X	X		X
M558	Radioactive Tracer		X	X		X
M559	Microsegregation in Germanium		X	X		X
M560	Growth of Spherical Crystals		X	X		X
M561	Whisker-Reinforced Composites		X	X		X
M562	Indium Antimonide Crystal Growth		X	X		X
M563	Mixed III-V Crystal Growth		X	X		X
M564	Halide Eutectics		X	X		X

Table II.0-1. (continued)

NUMBER	EXPERIMENT TITLE	DEVELOPMENT RESPONSIBILITY		INTEGRATION RESPONSIBILITY		COROLLARY EXPERIMENT
		MSFC	JSC	MSFC	JSC	
M565	Silver Grids Melted in Space	X		X		X
M566	Aluminum-Copper Eutectic					
S009	Nuclear Emulsion	X		X		X
S015	Effect of Zero-gravity on Single Human Cells		X		X	X
S019	UV Stellar Astronomy		X			X
S020	UV/X-Ray Solar Photography		X			X
S052	White Light Coronagraph	X		X		
S054	X-Ray Spectrographic Telescope	X		X		
S055	UV Scanning Polychromator Spectroheliometer	X		X		
S056	Dual X-Ray Telescope	X		X		
S063	UV Airglow Horizon Photography		X			X
S071	Circadian Rhythm, Pocket Mice		X(ARC)		X	
S072	Circadian Rhythm, Vinegar Gnats		X(ARC)		X	
S073	Gegenschein/Zodiacal Light	X		X		
S082A	Extreme UV Spectroheliograph	X		X		
S082B	Ultraviolet Spectrograph	X		X		
S149	Particle Collection	X		X		
S150	Galactic X-Ray Mapping	X		X		X
S183	Ultraviolet Panorama	X		X		X
S190A	Multispectral Cameras	X	(France)	X		X
S190B	Earth Terrain Camera		X	X		
S191	Infrared Spectrometer		X	X		
S192	Multispectral Scanner		X	X		
S193	Microwave Radiometer/Scatterometer & Altimeter		X	X		
S194	Microwave L-Band Radiometer		X	X		
S201	Far UV Electronic Camera	X		X		X
S228	Trans-Uranic Cosmic Rays	X		X		X
S230	Magnetospheric Particle Composition	X		X		X
S232	Barium Plasma Observations	X		X		X
S233	Kohoutek Photometric Photography				X	X

Table II.O-1. (continued)

NUMBER	EXPERIMENT TITLE	DEVELOPMENT RESPONSIBILITY		INTEGRATION RESPONSIBILITY		COROLLARY EXPERIMENT	
		MSFC	JSC	MSFC	JSC		
T002	Manual Navigation Sightings Inflight Aerosol Analysis Crew/Vehicle Disturbance Foot-Controlled Maneuvering Unit Coronagraph Contamination Measurement Contamination Measurement Earth Laser Beacon	X(ARC)		X		X	
T003		X(DOT)		X		X	
T013		LaRC		X			X
T020		LaRC		X			X
T025			X		X		X
T027				X(GSFC)	X		X
T053							
TOTAL EXPERIMENTS - 94		59	35	88	6	64	
OPERATIONAL INSTRUMENT							
	Proton Spectrometer	X		X			

y extracted from the PI's original proposal, but updated to the current status. The EIP was preliminary in nature, and to determine program impact in each discipline. The document was prepared for one-time use only and was not updated after the experts approved for flight. The EIP provided initial requirements in the experiment compatibility assessment.

A compatibility assessment was conducted by SL-DP to determine what would be feasible to fly the experiment on Skylab. The assessment determined the following experiment requirements to determine compatibility with Skylab capabilities and impact on Skylab subsystems:

- Mechanical
- Weight and stowage
- Consumables
- Electrical
- I&C
- Environments
- Materials
- Contamination
- Photography
- Experiment and cluster pointing
- Safety
- Systems test
- GSE, facilities
- Flight plans
- Crew interfaces

The compatibility assessment also made recommendations for the experiment age and operational locations, preliminary interface definitions, acts to timelines, etc. It was necessary in some cases to modify the EIP as a result of the compatibility assessment. Such changes were coordinated with the PI before presentation to the MSFEB. In other cases, minor modifications to the vehicle were recommended to accommodate the experiment.

The compatibility assessment and the EIP were jointly presented to the Director at NASA Headquarters for approval. Once the MSFEB and the Director approved the experiment for flight, the EDC proceeded with the selection of an experiment developer (ED) and initiated preparation of a preliminary Experiment Requirements Document (ERD).

The ERD defined the experiment requirements to be met by the Sky-Lab, including an experiment description and mission assignment, payload data, flight vehicle systems, pointing, postacceptance test-supply requirements. The preliminary ERD used the EIP and compatibility assessment, as modified by MSFEB, for initial information. The ERD was expanded through coordination with PIs, EDs, and experts in the various subsystems affected to provide a single, authoritative source of experiment requirements.

The ED's design concepts and the preliminary ERD were reviewed at the PRR. At completion, approval was given to begin the experiment hardware design, contingent on the closure of applicable RID. The ERD was baselined by the intercenter Level II CCB after all ERD RIDs had been closed.

The PRD was the first formal design review for the experiment hardware. At this review, the ED presented the preliminary hardware design approach to meet the experiment requirements approved at PRR. Each PDR resulted in either approval of the design approach or the generation of RIDs against the design. Review participation was provided by all affected NASA centers, NASA Headquarters, and affected contractors. The PDR end result, after successfully completing all actions, was NASA's approval to proceed with detailed hardware design.

A CDR was held when detailed hardware design documentation and development testing were essentially complete. The CDR was the last formal design review, ultimately approving and baselining the detailed design for hardware fabrication. The CDR was conducted in the same manner as the PDR.

After baselining (and throughout subsequent program phases when applicable), any necessary hardware design or documentation changes were assessed for total program impact and a complete change package submitted to the appropriate CCB for approval. Where multilevel or intercenter CCB action was involved, the actions were pre-coordinated to provide the necessary sequential or concurrent CCB directions and approvals.

2. Fabrication, Design Verification, and Acceptance. The ED fabricated experiment hardware normally included mockups, prototype hardware, a qualification unit, a flight unit, a flight backup unit, and training hardware. Mockups were used for PDR and CDR. Prototype hardware was used, as required, for development testing.

After successful completion of the CDR, the ED fabricated and tested a qualification unit, using the same design, materials, and processes as for the flight unit. In many cases qualification test results necessitated hardware redesign or modification to meet the test requirements. Where experiment hardware could not readily be modified to meet qualification test requirements (e.g., electromagnetic interference, touch temperatures, etc), waivers were submitted for review by the EDC. Each waiver was evaluated individually and approval was usually granted where workarounds or corrective actions could not readily be accomplished within cost or schedule limitations, providing safety was not affected. When qualification test results were approved by NASA, a Certification of Qualification was issued, certifying the hardware design for Skylab use.

The flight and flight backup units were usually fabricated in parallel with the qualification unit. The qualification unit, in some

series of formal Postacceptance Test Requirements and Specifications (PATRS) meetings. The meeting results were formalized in the Experiment Integration Test Requirements and Specifications (EITRS) document.

The module contractors used the EITRS as inputs to the TCRSDs that governed the experiment test activities at their facilities. Each module contractor developed test and checkout procedures based on requirements defined in the TCRSDs. Experiment tests at the module contractors' facilities were monitored and supported by SL-DP.

The flight experiment hardware was shipped to KSC in one of several ways: on module, removed from the module and shipped separately, returned to ED (for further testing, repair, calibration, upgrading, etc.) and then shipped, or sent to another module contractor for fit checks before being delivered to KSC. Upon arrival at KSC it underwent receiving and inspection before any testing. KSC test plans and procedures were reviewed by SL-DP to assure compliance with the TCRSDs. The actual tests were monitored and support provided in tracking and closing out of Discrepancy Reports.

b. Systems/Operations Compatibility Assessment Review. The SOCAR was conducted in the time period of February through June 1972 to assess

(1) the Skylab systems design, integration, and performance characteristics, based on updated engineering analyses, simulations, and actual hardware test experience, and

(2) the operational readiness of Skylab through a detailed review of the mission plans, procedures and documentation to be used by the operations team for the conduct of the mission.

An MSFC corollary experiments team, under SL-DP direction, participated in direct coordination with the JSC corollary experiment flight control team.

c. Design Certification Review. The MSFC corollary experiment DCR was conducted, as required by Skylab Program Directive 11a, to examine the experiment hardware design and design verification program to assess and certify that the experiment hardware could accomplish the planned Skylab missions. Specific objectives of the review were to:

(1) Certify the experiment hardware design for manned flight safety.

(2) Certify the experiment hardware design for flight worthiness.

The DCR was conducted in 5 phases during the period April 1972 through October 1972, culminating in a final report and an oral presentation to NASA management for each experiment.

Several experiments were approved late in the Skylab Program and were not covered during the formal MSFCs corollary experiments DCR. These included the Student Project experiments; the Multipurpose Electric Furnace Experiments; Experiment S228, Trans-Uranic Cosmic Rays; and experiment S230, Magnetospheric Partical Composition. The same DCR activities and certification were accomplished for these experiments, except that formal oral presentations to NASA management were not made.

d. Flight Readiness Review. The MSFC corollary experiment FRR was part of the overall Skylab Program FRR as required by Skylab Program Directive 59. The FRR assessed the operational readiness and safety of all the experiment flight hardware and adequacy of documentation. There were three FRRs conducted; SL-1/2 on April 19, 1973, SL-3 on July 19, 1973 and SL-4 on October 18, 1973.

4. Mission Support. The corollary experiment mission support group was responsible for all activities associated with the evaluation of MSFC corollary experiment operations, the assessment of experiment hardware performance, and the integration assessment of experiment support systems. All activities were performed in support of the MSFC corollary experiment manager in the Flight Operations Management Room (FOMR) at JSC. This interface was maintained through the HOSC.

The MSFC mission support activities were centralized at the HOSC. The HOSC provided a monitoring and evaluation function for all MSFC-managed spacecraft systems and associated anomaly resolution. The HOSC served as the central organization through which all JSC requests for assistance were received and processed.

Support personnel (experiment teams) monitored all operational data and information affecting experiment performances. The activity included: daily reviewing of flight plans and Pre-Advisory Data (PAD) to ensure experiment requirement compliance; monitoring flight director and air-to-ground voice loops to anticipate anomalous situations; constantly reviewing vehicle systems status for possible experiment impact; and assessing all real-time change paper to ensure experiment compatibility.

The experiment accomplishment status was maintained throughout the mission and flight planning recommendations were prepared twice weekly for use by the SL-DP Manager at the semi-weekly Science Planning Conferences at JSC.

Experiment team requirements for real-time telemetry measurement data were satisfied by HOSC support personnel who obtained printouts from the MOPS computer network. The telemetry data was required to assist the experiment teams in assessing hardware performance, interface verifications, and constraint compliance.

The experiment teams generated daily experiment operation inputs to the HOSC report, which was submitted to the FOMR for review and

incorporation into the JSC daily report. The experiment teams provided inputs to other MSFC reports and summaries in which corollary experiments were involved.

The experiment teams continually assessed mission operations for potential or real problems. When a problem was identified, the team investigated the circumstances and generated appropriate recommendations for anomaly resolution.

Experiment teams responded to JSC or HOSC queries when assessment of hardware operation, malfunction procedures or operational workarounds were being considered. Investigations and/or special studies were conducted as required, and formal responses to the queries were processed through the MSGL and the HOSC.

Scientific impact problems were evaluated with the PI. These problems were typically those involving changes in time allotted to an experiment, or any problem that might affect the quality of the scientific results.

5. Data Analysis and Reporting. A majority of the experiment scientific data have already been disseminated to the PIs at this writing, and their data analyses are in process. Generally, the PIs are obligated to publish interim and final reports of their experiment results - the final output being either a formal NASA report or a paper in an appropriate scientific journal. The PI participation in the various symposia and seminars being sponsored by Government agencies and the scientific community is encouraged by SL-DP, which is coordinating all these reporting activities with the PIs.

The NASA EDCs are concurrently preparing Mission Evaluation Reports, covering the hardware performance of their experiments and the degree of compliance with operational constraints and systems interface requirements during the mission.

An integrated set of hard bound books reporting Skylab results is being prepared by MSFC and JSC for publication by the Government Printing Office as NASA Special Publications.

P. Ground Support System

The Ground Support System for the Skylab Program consisted of all the GSE necessary to support systems tests and prelaunch activities of the SWS and its hardware. The concept of GSE provisioning was complex in nature due to the wide variety of requirements that had to be satisfied and the large number of contractors involved. Many requirements were peculiar to individual flight hardware (experiment and module) and of necessity required unique provisioning. Other requirements, primarily flight systems testing, economically dictated the use of common GSE designed to satisfy the worst case SWS configuration. The integration of total SWS requirements necessitated the consideration of individual module and experiment requirements, geographical locations and associated SWS configurations, availability of GSE at any given time, and logical assignment of GSE build responsibility to minimize impact on the test programs. Management of this integration effort was controlled to assure that all SWS requirements were satisfactorily met and within a compatible timeframe. The following paragraphs discuss in more detail the significant efforts involved, a summary of their effectiveness, and recommendations considered necessary for application on future programs.

1. Design Requirements. The development of design requirements for the Ground Support System for SWS elements involved extensive review analysis, and coordination of requirements identified in CEI specifications and TCRSDs. No formal CEIs were used to define contractually GSE required to support SWS requirements. Instead, identification of GSE was contained in descriptive documents provided by the various module contractors and by MSFC for experiment GSE. These documents essentially contained functional descriptions, illustrations, and site use effectivities for respective GSE and are identified as follows:

- OWS GSE - GSE Summary, Orbital Workshop
- MDA GSE - MDA GSE Description Document, ED-2002-2002
- Airlock GSE - AM GSE Index, 6IE000001
- ATM GSE - ATM GSE Requirements, 50M04954
- Experiment GSE - Skylab Experiments GSE Allocation Plan, 68M00005

The effort to identify specific design requirements for the Ground Support System was essentially a building block process and can be broken into pre- and postacceptance phases of the flight hardware involved. The individual contractor provisioned GSE required to support preacceptance activities on a unique basis as testing experience evolved and use beyond this phase was limited to those flight hardware requirements that remained peculiar through SWS build-up.

The postacceptance phase presented a more complex problem for hardware was scheduled to flow from geographical location to geographical location and test requirements changed as various flight hardware elements

became integrated in single configurations during SWS buildup. Individual requirements such as test and checkout, storage, handling, and transportation, as imposed on the Ground Support System, were also more complex and demanded that these requirements be integrated to the extent that individual contractor responsibilities were explicitly defined and maximum use of GSE was obtained.

It was recognized early in the program the need to identify and consolidate experiment requirements to establish facility and GSE design requirements for the total Skylab program. An integration task team(s) was organized to perform the necessary analysis for each experiment to determine functional support requirements at all applicable test locations. Individual meetings identified as PATRS meetings were scheduled as required for each experiment and ultimately resulted in the specific identification of the facility and GSE design requirements.

These requirements were then integrated into the Skylab Experiment GSE Allocation Drawing. The experiment analysis effort in combination with module level analysis provided decision making criteria as follows:

- GSE functional requirements
- Facility storage and environmental requirements
- Design parameters for handling, transportation, and environmental GSE
- Site effectivities by requirement and SWS configuration

With the above criteria established, the assignment of contractual responsibilities was accomplished on a more logical and economically feasible basis and minimized the possibility for duplication of GSE and/or the overlooking of a valid requirement.

2. Interface Requirements. The requirement to document GSE interfaces, both functionally and physically, was recognized early in the Skylab program. During 1969, tasks were contractually assigned to Martin Marietta Aerospace and General Electric Company to prepare and maintain the necessary Interface Control Documents to define total fluid, mechanical, and electrical requirements for the MSFC Ground Support System at KSC. This documentation included MSFC/KSC, MSFC/SWS, and MSFC/JSC interface definition. Resultant interface documents were contractually implemented between the NASA centers involved and subsequent changes were controlled through formal Interface Revision Notices (IRNs) on a contractual basis.

The development of interface definition initially required the formulation of basic system level ICDs to assure overall functional compatibility between the facility, GSE, and SWS modules. Identification of functional requirements essentially involved the following:

- System configuration (block diagram and hardware identification)
- Commodity specifications (pressure, flow rate, power levels, etc.)

- Hardware criteria (materials, construction, etc.)

The second phase of ICD development required a specific identification of physical and unique requirements at the GSE end item level and basically consisted of the following information:

- Physical interface hardware identification, location, and responsibilities.
- Footprint, access, and installation requirements for individual items of GSE.
- Environmental and storage requirements.

The implementation of interface requirements was complex in nature due to the variety of requirements and the large number of contractors involved and it necessitated a disciplined plan to achieve a contractual baseline on a timely basis.

The implementation plan consisted of three essential phases as outlined below:

a. Phase I. Development of Requirements

(1) Research documents, drawings, or other data necessary for preparing ICDs.

(2) Prepare sketches and/or layouts as required to determine space, access and handling requirements.

(3) Perform liaison with the appropriate MSFC/JSC/KSC agency and module/experiment contractors.

(4) Attend meetings with subpanels, working groups, design reviews, etc., to identify impact on interface requirements.

(5) Review and evaluate ECPs, ECRs and CRs.

b. Phase II. ICD Preparation

(1) Prepare ICDs

(2) Contractually implement ICDs

c. Phase III. ICD Maintenance

(1) Prepare and process emergency and routine IRNs.

(2) Contractually implement IRNs.

No formal GSE interface documentation was imposed on participating contractors involved in activities at St. Louis, Huntington Beach, Huntsville, Denver, etc. Informal documentation was prepared in some

instances where interfaces were complicated and a working baseline was required.

3. Compatibility Analyses. The SWS requirements for fluid and pneumatic servicing and checkout at KSC involved an extensive amount of GSE to provide a Ground Support System of sufficient capability and versatility to meet these requirements. Basic GSE provisioning involved equipment elements that were used as a system for the first time during the KSC Verification Program.

The integration of the overall Ground Support System to insure that both system capability and compatibility existed with the SWS and its elements prompted the center to authorize a technical evaluation task at the end item level. The total fluid and pneumatic systems were reviewed to identify critical items of GSE in the systems and analyses efforts were conducted as follows:

- a. System design requirements versus hardware.
- b. System design capabilities including:
 - Media
 - Flow Rate
 - Pressure or Vacuum
 - Temperatures

Data sheets on selected critical end items were prepared and included analyses results along with appropriate recommendations for any noted incompatibilities. Emphasis was placed on minimizing impact on flight hardware.

The results of this integration effort proved fruitful because some incompatibilities were discovered and appropriate disposition of these problems was accommodated within a time frame compatible with program schedules.

4. Safety Criteria. Individual items of GSE required to provide a total Ground Support System at KSC were basically derived as new GSE, modified GSE, or existing GSE, which included Government Furnished Equipment. Experience from previous programs dictated the need to provide a method of assessing this GSE in terms of design features as related to systems failure, equipment damage, and personal injury. The effort was initiated to provide the safety assessment means that included essentially a three phase operation.

The initial phase involved the assessment of program level requirements and GSE design criteria to develop a safety criteria in checklist format. The checklist criteria was organized into three checklist sections; namely, liquids and gases, electrical/electronics, and handling and transportation. This information was published as the Skylab System Safety Checklist, SA-003-001-2H, dated July 1971.

Phase II of the safety assessment program required that individual contractors assess each item of this GSE to be used at KSC against the three checklist criteria and indicate compliance, noncompliance, or not applicable. Completed checklists with appropriate signature approval sheets were then processed on a periodic basis.

Because the System Safety Checklist document did not impose requirements on GSE but merely provided for an assessment, the third phase of the total effort required processing of all contractors inputs by MSFC as part of a systematic safety assessment program. The evaluation of this information provided the center with the necessary information to identify safety conditions and implement corrective action.

5. Contingency Operations. The original intent of the KSC Verification Program evolved around a "green light" philosophy using the concept of flight hardware replacement at the black-box level. Additionally, once SWS closeout was accomplished in the Vertical Assembly Building (VAB), there was no consideration for reentering the SWS at the launch pad on a contingency basis.

As the complexity of flight hardware and the SWS configuration increased, the need to provide certain capabilities on a contingency basis was recognized. Basic analysis efforts at the module contractor and center level were initiated to assure that minimum impact on the launch schedule was imposed if contingencies should arise.

Basic ground rules on contingency analyses were established as follows:

a. Provide the necessary GSE to remove and replace flight hardware on a contingency basis during operations in the O&C building and VAB. These analyses efforts and the associated implementation of GSE requirements were essentially accomplished at the module contractor level. The primary consideration that paced analyses efforts was to assure that for a given item of flight hardware to be removed the following evaluation criteria and GSE provisioning was satisfied:

(1) Evaluation Criteria

- Criteria for removal versus in-place maintenance.
- Clearances
- Weight
- Personnel and equipment safety
- Contingency procedures
- Timeline

(2) GSE Provisioning

- Access - platforms, handrails, etc.
- Handling - attachments, lifting, safety covers, etc.
- Transportation - dollies, track assemblies, etc.

Contractor study results were reviewed to determine compatibility of recommendations with program guidelines on flight hardware replacement. In many instances, GSE was provisioned as the result of this review for strictly contingency use.

b. Perform an analysis to define all requirements for access in the event a program decision was made to enter the SWS at the launch pad on a contingency basis. The results of this analysis were documented as "Access Operations Data - Launch Pad 39", (SA-001-006-2H) dated November 1970. This study did not attempt to define the reasons for access, but limited itself to the basic mechanics of how to achieve such entry in the most expeditious manner. Basic considerations were as follows:

- Access routes
- Environmental considerations
- Personnel safety
- GSE and facility requirements
- Facility configuration
- Timeline
- Sequence of activities

The recommendations as a result of this effort presented primary and alternate access routes on the basis of dividing the SWS into physical zones.

6. Conclusions and Recommendations. The effectiveness of the above efforts to provide a Ground System that satisfied total program requirements is considered on a general basis to be satisfactory. Major program milestones were supported and the ultimate success of the SWS during mission operations directly reflects the success of Ground Systems.

No program, however, is completely free of problems and lessons learned should be identified as a means to aid future programs. Specifically, recommendations considered to be of significant importance for future applications and associated rationale are identified below:

a. Recommendation. Provide Contract End Item Specifications at the contractor level for Ground Support System elements.

Rationale. The development of design requirements involved extensive coordination and analysis efforts to achieve a design baseline. The lack of formal contractual baselines for GSE design requirements resulted in certain costly requirements such as contingency removal and replacement of flight hardware being identified late in the program and thus required expedited implementation. The consideration of GSE CEI specifications would lead to a more realistic review of requirements early in the program and would significantly reduce costs because program management visibility across many contractors would be increased in a more practical time frame. Standardization of design requirements and maximum utilization of equipment to satisfy common requirements are obvious benefits.

b. Recommendation. Impose the requirement to develop contractual ICDs (GSE to GSE) for each site where major verification programs involving two or more contractors exist.

Rationale. The only contractual interface baseline for GSE on the Skylab program was at KSC. Although KSC involved NASA center to center interfaces and numerous contractors, the essential purpose of a contractual interface agreement evolves around establishing both requirements and responsibilities and subsequent agreement. This primarily applies to contractors and is independent of NASA center-to-center relationships.

III. Integrated Test Program

SECTION III. INTEGRATED TEST PROGRAM

A. Introduction

1. Purpose. This section of the Final Report will discuss, in general terms, the integrated test program from concept through launch. Philosophy, as well as the finalized test program, will be covered. The last section will offer conclusions and recommendations based on results of the total integrated test program.

2. Scope. The majority of coverage will be a discussion of the actual tests as they were performed, starting with design verification development/qualification tests, pure qualification testing, proceeding with flight hardware verification, and concluding with the KSC test program through launch. Actual test details will not be included, but references to test reports, where applicable, will be made. Conclusions and recommendations will be found in the final paragraph of this section.

3. Summary. The Skylab program demonstrated the feasibility of developing separate space station modules, at different locations, for assembly and integrated design verification testing at the launch site or other central location. To accomplish this the test program was designed to verify performance requirements through a progressive building block technique which included the following:

- Component/experiment bench test,
- Subassembly tests,
- Experiment integration tests,
- Individual systems tests,
- Combined module systems tests,
- Multimodule integrated systems tests,
- Cluster integrated systems tests,
- Spacecraft to launch vehicle tests.

To assure the verification activity was adequate and economically realistic, it was developed, controlled, and continuously evaluated on a total system basis. Systematic analyses of design requirements and subsystem designs were made to identify only those tests essential for verification.

The verification program was identified and defined in module test plans and other lower level test plans. Detail TCRSDs were developed for the module level acceptance test program and for module and integrated testing at KSC. These TCRSDs formed the basis for the preparation of formal approved test procedures.

Test compliance was established on the module and cluster system levels. Final cluster systems acceptance was accomplished by means of

the Skylab Intercenter Test Results Review held at KSC just before Flight Readiness Review.

Conclusions and recommendations are presented in the following general categories:

- Test planning,
- Test requirements,
- Test procedures
- Test teams,
- Test scheduling,
- Test program evaluation,
- Mission support testing.

B. Verification Program Philosophy

1. General. The Skylab Verification program was designed to provide complete verification and establish a high level of confidence in the cluster hardware flight readiness at minimum program cost. The Skylab program design and performance requirements, as defined in the Cluster Requirements Specification, the module Contract End Item Specifications, and the individual experiment Contract End Item Specifications, were satisfied by the verification method of test and/or assessment. The principles of system engineering analysis were used to translate these design and performance requirements into verification requirements.

The general ground rules and guidelines for development of the Skylab test program were:

- All system malfunctions corrected or satisfactorily explained and accepted to certify flight readiness;
- Equipment performance to be uncompromised by functional tests;
- Equipment removal for tests minimized;
- Duplication of testing minimized;
- Equipment test time minimized and time/cycle data recorded for time/cycle critical components;
- Appropriate reverification required if equipment or overall configuration was changed after test.

The test program for the Skylab flight hardware was designed to verify performance requirements through a progressive building block technique which included the following:

- Component/experiment bench level acceptance test;
- Testing of selected subassemblies consisting of several functional components/experiments;
- Experiment integration tests to verify experiment to module system compatibility;
- Individual system testing using mating module simulators;
- Combined module systems testing using mating module simulators;

- Multimodule integrated systems testing (AM/MDA and CSM-AM/MDA);
- Cluster level integrated system testing;
- Prelaunch checkout with launch vehicle.

During each phase of testing, any problems encountered were resolved and retested before proceeding to the next phase of testing. If unique problems existed where this was not possible, then acceptable workaround plans were developed and executed to ensure system confidence.

Simulators were used to a large degree in the early stages of test. These were designed to simulate inputs and responses of those Skylab modules not present for the test activity. As the test program progressed, the use of simulators decreased. These simulators allowed full systems checkout with a high degree of realism, and served to provide confidence in complete systems performance during the launch site activity.

The simulators used were not of the level one type, i.e., nearly exact reproductions of those systems they simulated. However, the level of simulation was adequate for the objective of obtaining confidence in orbital vehicle systems performance.

The Skylab program was unique in that there was a significant amount of first-time testing being accomplished at KSC. There were no flight-type prototypes available to verify the many functional interfaces between the various modules. As a result, a comprehensive module and multimodule test program was required at KSC.

In addition to the first-time testing at KSC, there were many functions that were never verified end-to-end during the flight hardware test program, because of the complexity of the facilities required for the testing or the impracticality of performing the test on the ground. A combination of analysis, nonflight hardware testing, and flight hardware testing with interface simulators was used to verify the particular function and ensure total system verification at a minimum cost. Some of the more significant first time-on-orbit operations for flight hardware follow.

Deployment and Separation Systems

- ATM Rigidizing and deployment
- ATM Solar Array deployment
- OWS Solar Array deployment
- Payload shroud jettison
- OWS Radiator plume shield jettison

Electrical Power System

- Parallel Operations
- Single Point Ground and power transfer

Instrumentation/Communication System

- Audio system end-to-end
- Television end-to-end

Guidance

- Orbital maneuvers

2. Verification Program Definition and Control. To assure the verification activity was adequate and economically realistic, it was developed, controlled, and continuously evaluated on a total system basis. Systematic analyses of design requirements and subsystem designs were made to identify only those tests essential for verification. This effort included:

- Criticality Assessment. It was imperative that critical hardware and critical interfaces be identified early by failure modes and effects analyses and related design assessments to focus test program requirements on the mission critical and crew safety aspects, and to assure proper concentration of program resources.
- Optimum Test Articles. Strong systems management concepts and detailed analyses were imposed in order to reduce the number of test articles built specifically for development and qualification. Qualification at the highest practical assembly level was considered.
- Optimum Test Flow. Systems management concepts were also imposed to emphasize the cradle-to-grave approach. This approach was necessary to minimize redundant tests at all levels.

The verification program was identified and defined in module and other lower level test plans. As the verification program progressed, the top level plans were updated to incorporate the latest program direction.

During the course of the verification program definition, considerable Intercenter data coordination and interchange was required. In support of the KSC prelaunch and launch operations, the MSFC-Skylab Program furnished documentation for development of KSC test plans and procedures and establishment support required for Skylab launch operations.

This documentation included TCRSDs, ERDs, ICDs and Acceptance Data Package (ADP) per module. This documentation established the minimum test requirements as identified by MSFC to be satisfied at KSC.

3. Test Requirements and Specifications

a. General. The Skylab Program TCRSDs were developed in the building block concept. The TCRSD was developed for the modules to

verify system operation in accordance with the module end-item specification. Additionally, experiment checkout requirements for on-module testing were included. These TCRSDs were the basis for checkout procedures and factory acceptance testing. Such documents were invaluable in establishing contractual compliance.

An integrated cluster systems TCRSD was developed to define test and checkout requirements for the integrated Skylab cluster systems at the launch facility. This was accomplished by the formation of cluster systems test requirements review teams composed of technical experts from the NASA design organizations, systems engineering organizations, program offices, KSC test offices, and contractors. Upon technical agreement by each of the system teams, the integrated TCRSD and the module TCRSDs were baselined and controlled by the Level II Configuration Control Board. These baselined TCRSDs provided the technical basis for the final test and checkout plans and procedures at KSC.

Upon delivery of modules from the factory to KSC, representatives from each of the system teams (both NASA and contractor) were assigned to KSC to maintain the TCRSDs. Required changes to the TCRSDs were implemented and controlled by the test change notice system, which was controlled and approved by the Level II CCB at KSC. These teams and the TCN board were responsive to the KSC test schedules.

b. Module Level General Test Requirements. The general test requirements for the module level test program follow

(1) Post-manufacturing checkout will be performed to verify that the end-item hardware conforms to the applicable specifications for the performance and configuration as a basis for module acceptance;

(2) Post-manufacturing checkout will be successfully completed before assembly into higher hardware generation level at another contractors plant or NASA installation site.

(3) Include testing in environments other than ambient when analysis is insufficient to verify performance of the hardware.

(4) Verify functional operation of primary and redundant components/systems. Special emphasis will be given to Category 1 and 2 primary and redundant (when possible) components/systems.

(5) Verify that the end-item meets the performance/design requirements of the CEI Specification, including physical and functional mating compatibility with flight and ground support equipment, as applicable.

(6) Experiments will be installed in flight modules at the module build facility and will be functionally verified to the extent necessary to verify module to experiment interfaces and operational compatibility.

(7) Post-manufacturing test will be conducted by the contractor with Center-approved applicable test requirements.

c. Multimodule General Test Requirements. The general test requirements for the multimodule level test program follow

(1) Multimodule tests will be used for acceptance at higher levels of assembled hardware and will verify that all flight systems meet performance requirements as an integrated "system" and are physically, functionally, and operationally compatible with mating hardware systems, and ground support systems.

(2) Testing previously conducted at a lower hardware level will not be duplicated unnecessarily by multimodule tests.

(3) Multimodule tests will validate interface performance/design requirements that cannot be verified at the level of the individual end-item.

(4) Electromagnetic Compatibility. The performance of integrated modules will not be degraded by electromagnetic incompatibility during any ground test.

(5) Man-machine tests will be conducted to verify procedures and crew ability to perform mission objectives.

(6) Verify compatibility of all cluster systems to operate simultaneously as required by mission usage.

(7) Verify all planned primary and backup operation modes only.

d. Cluster System General Test Requirements. The general test requirements for the cluster level integrated systems testing and pre-launch checkout follow

(1) Checkout tests will verify that the SWS will meet countdown, launch, and orbital performance requirements as a totally integrated system, and that the SWS is physically, functionally, and operationally compatible with SL-1 launch vehicle, GSE, and launch facilities.

(2) Perform complete visual receiving inspection to ensure satisfactory physical condition of the hardware before assembly and test.

(3) Verify module interface compatibility to assure interactions between modules are within specification limits.

(4) Perform functional checkout of the SWS, launch vehicle to SWS interfaces, GSE, and facilities.

(5) Perform tests that exercise systems sequentially in normal operating and selected contingency modes for periods sufficient to verify mission capabilities. Tests will include parallel operation of the ATM/AM electrical power systems.

(6) Perform electromagnetic interference test to verify compatibility of assembled modules per applicable sections of specification MIL-E-6051.

(7) The dimensional fit of interconnecting mechanical and electrical module interfaces will be demonstrated during the stacking operations of the SWS modules.

(8) Perform verification, to the maximum extent practical, of functional operation of all redundant subsystems and their elements before launch. The verification will be limited to flight hardware and mission-essential GSE. Special emphasis will be given to criticality Categories I and II items.

4. Test Implementation. All system level acceptance test requirements were performed in accordance with formal approved test procedures. The names and format of the procedures varied based on the contractor and/or test location, but all served the same purpose; that of formally documenting detail test operations based on approved test requirements and specifications. Formal procedure change control systems were used in revising or updating the procedures that conformed to the standard practice of the issuing organization.

5. Test Compliance

a. Module Acceptance. Each module contractor had his own method of verifying test compliance. At the time of module turnover reviews, Section 4 of the Module CEIs were reviewed and compliance verified and agreed upon. This included verification that tests were completed or carried forward to the next test location and also concurrence with the rationale for design and performance requirements being verified by analysis.

b. Cluster Systems Acceptance. The Skylab Program initiated a series of reviews that were handled by cluster system. These reviews started with the SOCAR and continued through DCR and FRR. The verification program, both test and assessment, was under continuous review during the working groups and formal presentations of these reviews. Final systems acceptance was accomplished by means of the Skylab Intercenter Test Results Review.

c. Skylab Intercenter Test Results Review. The Skylab test results review was conducted during March 26-30 1973, at KSC to provide a formal detailed final review of the KSC test program and test results. This review assisted in assessing the flight readiness of the Skylab Cluster System and experiments for launch. Teams were formed on a system

basis with representation from the test and design organization from each Center and the prime contractor to accomplish the following:

- (1) Verify KSC testing compliance with TCRSD requirements;
- (2) Verify adequacy of KSC mod kit validations including systems retesting;
- (3) Verify adequacy of component changeout validations including systems retesting;
- (4) Assess test results against systems specifications and criteria.
- (5) Assess disposition of IDRs, DRs, waivers, and deviations. Validate successful testing of all hardware single failure points.

Deficiencies were documented by MSFC via a "RID" form to KSC for disposition.

A Pre-Board Meeting was held on March 30, chaired by MSFC/MSK/KSC, to dispose of the RIDs and make recommendations to the Program Manager Intercenter Meeting held on April 2 and 3, 1973. The Intercenter Program Managers meeting disposed of the RIDs from the Pre-Board and received an overall briefing on the results of KSC testing. This was an important input for the FRR. Figure IILB-1 outlines the KSC test review process.

6. Backup Hardware Testing. The module backup hardware was subjected to a module level test program similar to the flight hardware test program. The backup hardware test program was planned so that if there were a catastrophic failure of the SL-1 hardware, the backup hardware would be ready to launch within ten months of the failure. The only multimodule testing was the AM/MDA testing at St. Louis.

For details of the module backup hardware test programs, refer to the following MSFC reports:

AM TMX-64810
MDA TMX-64812
OWS TMX-64813
ATM TMX-64811

At the conclusion of the module level acceptance testing (including AM/MDA), the backup hardware was maintained during the mission for mission support testing.

7. Mission Support Testing. Mission support testing consisted of many facets and included module backup hardware testing, cluster system breadboard/simulator testing, crew systems testing (NB, One-G, Zero G).

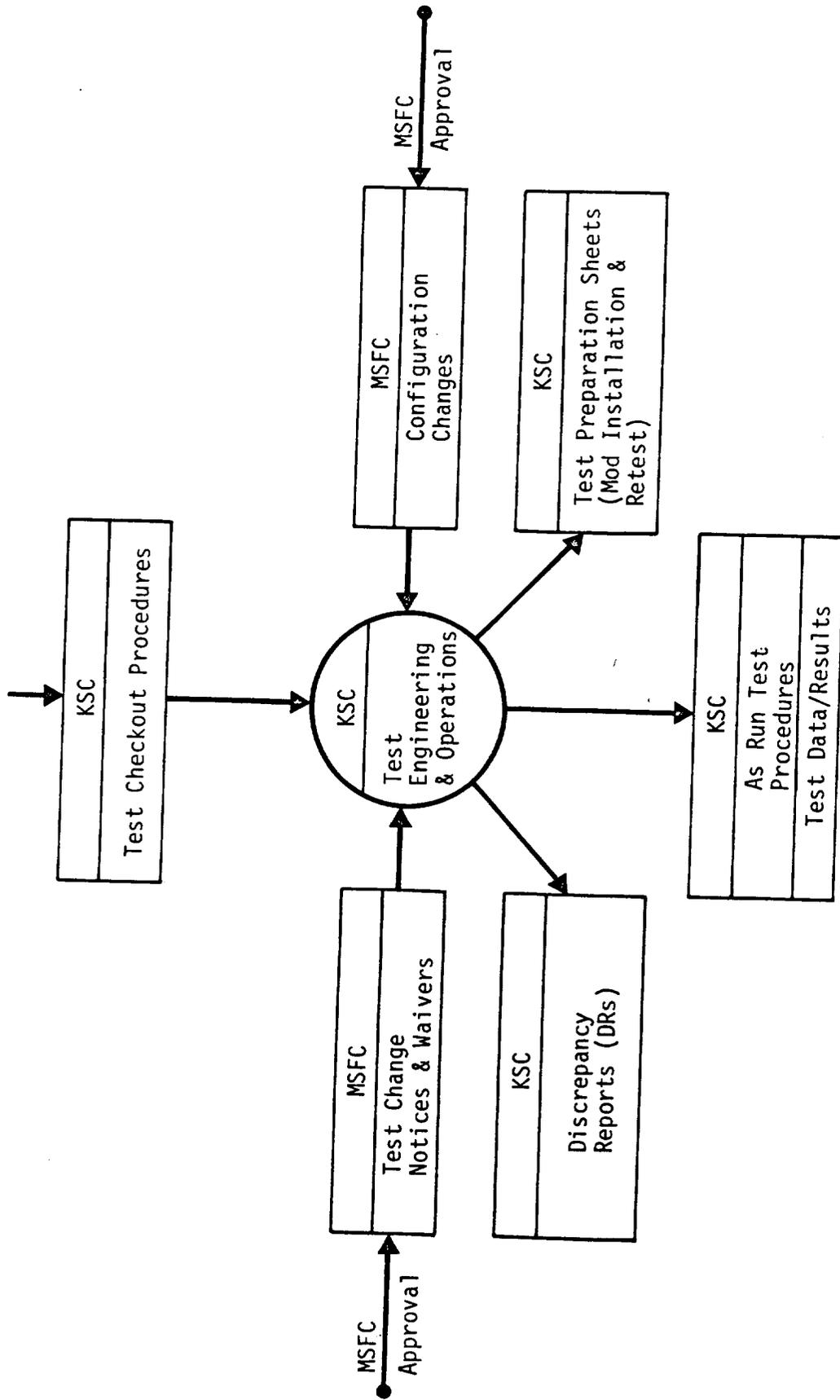


Figure III.B-1 KSC Test Review Process

Details of the mission support testing are found in the module level reports.

8. Post-Mission Engineering Tests. The Skylab spacecraft was subjected to a series of engineering tests (after splashdown of SL-4) to evaluate the reliability of some redundant systems, and to verify and/or troubleshoot previous failures. Following is a list of the post-mission test objectives.

- Attempt to spin-up CMG No. 1.
- Determine capacity of PCG batteries.
- Activate secondary refrigeration subsystem.
- Troubleshoot secondary coolant loop.
- CBRM power sharing test.
- Switch to redundant ATM TLM equipment.
- Attain gravity gradient attitude.
- ATM command receiver test.
- Load ATMDC No. 1 via MLU.

C. Design Verification

Design verification was performed to provide data to be used in support of the design of a specific component, subsystem, or system. Tests were also performed on prototype and production hardware to verify that flight hardware meets design specification requirements for operational suitability at anticipated environments deriving their use cycle.

The design verification test requirements for the Skylab Program were divided into two categories: development and qualification. Development tests will be identified as those tests performed to select parts and components, investigate the adequacy and optimization of the preliminary design, determine significant failure modes and effects, evaluate effects of varied stress levels, and select materials or determine compatibility. Qualification tests will be identified as those tests conducted as a formal demonstration of the design and performance adequacy of the production flight hardware design. Development test hardware was representative of flight hardware insofar as possible, but not necessarily identical to flight hardware. Qualification tests were performed using flight-type hardware that is identical in performance, configuration, and fabrication to the space vehicle flight hardware.

1. Major Cluster System or Module Development/Qualification Tests. This section identifies the major development/qualification tests accomplished on the Skylab Program, and includes the test objectives and a brief description of the test results. If the reader requires more detailed test results, the specific test report for each test is identified. Figure III.C-1 identifies the general span time of the major development tests listed herein.

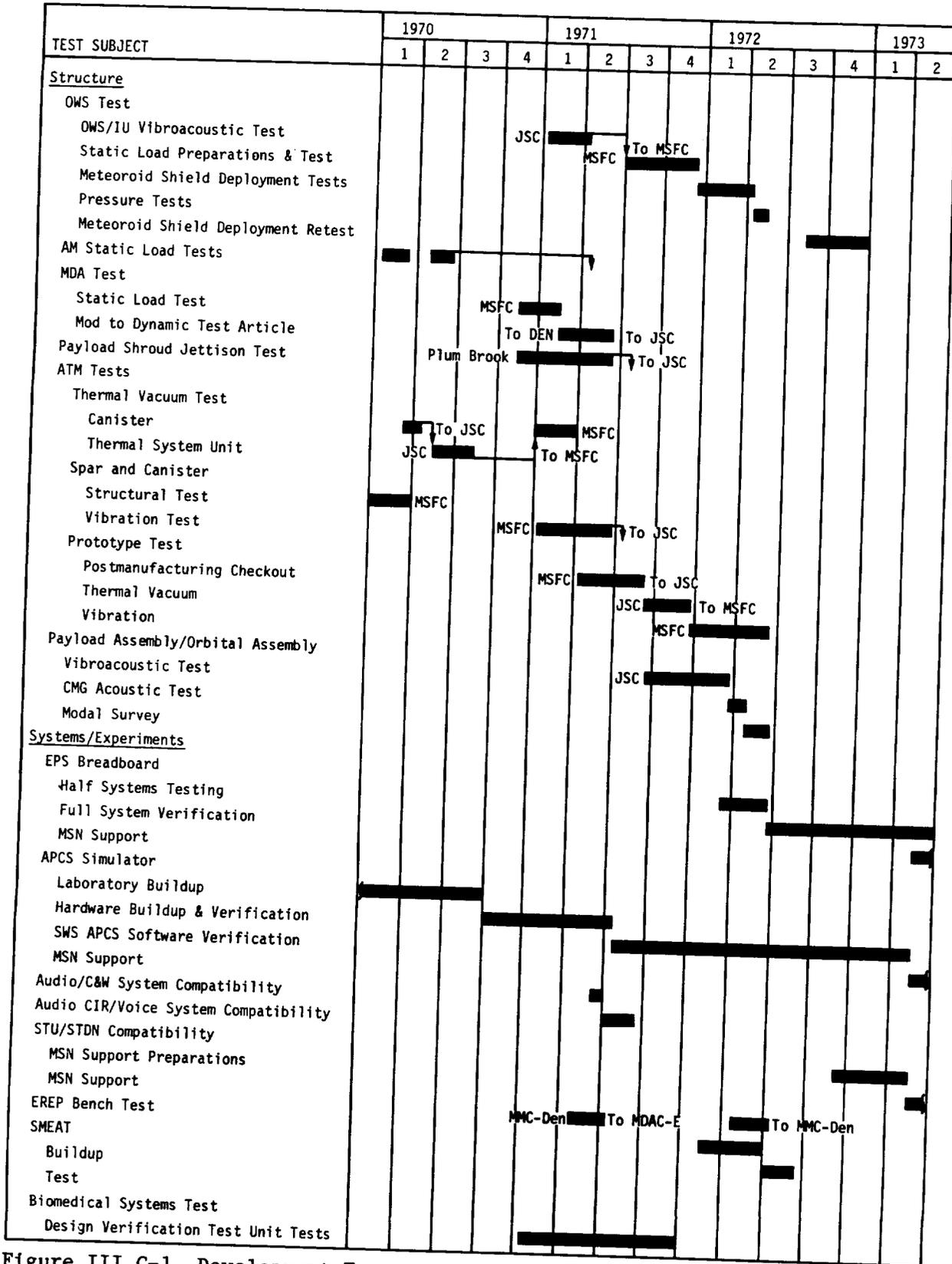


Figure III.C-1 Development Tests

a. Payload Assembly Vibroacoustic Test

(1) Test Location. JSC

(2) Test Objectives. The objectives of the test on Payload Assembly hardware follow and were as shown in Figures III.C-2 and III.C-3.

- Verify the dynamic design and test criteria for components and subassemblies;
- Verify the structural integrity of bracketry and secondary structure;
- Qualify selected flight hardware components.

The following test conditions were imposed on the hardware:

- Acoustics
 - Liftoff environment
 - Boundary layer environment
 - Special component tests
- Low Frequency Vibration (vehicle dynamics)

(3) Test Results. The acoustic and vehicle dynamics test of the payload assembly were completed with no failures of flight-type structure, either primary or secondary. Sufficient data were acquired to evaluate component qualification test criteria. Evaluation of these data resulted in the requirement to requalify a number of components.

Two special component tests were run as a result of previously conducted acoustic tests. The IU Flight Control Computer and the ATM Control Moment Gyro received separate special acoustic qualification tests.

Detail test results are contained in MSFC Report S&E-ASTN-ADD-72-29, dated January 1972.

b. Skylab Modal Survey Tests

(1) Test Location. JSC

(2) Test Objectives. The objectives of the tests on the Skylab hardware follow and were as shown in Figures III.C-4 and III.C-5.

- Determine the modal characteristics of the Skylab hardware in both launch and orbital configurations.
- Determine the dynamic characteristics of specific components and subassemblies in both launch and orbital configurations.

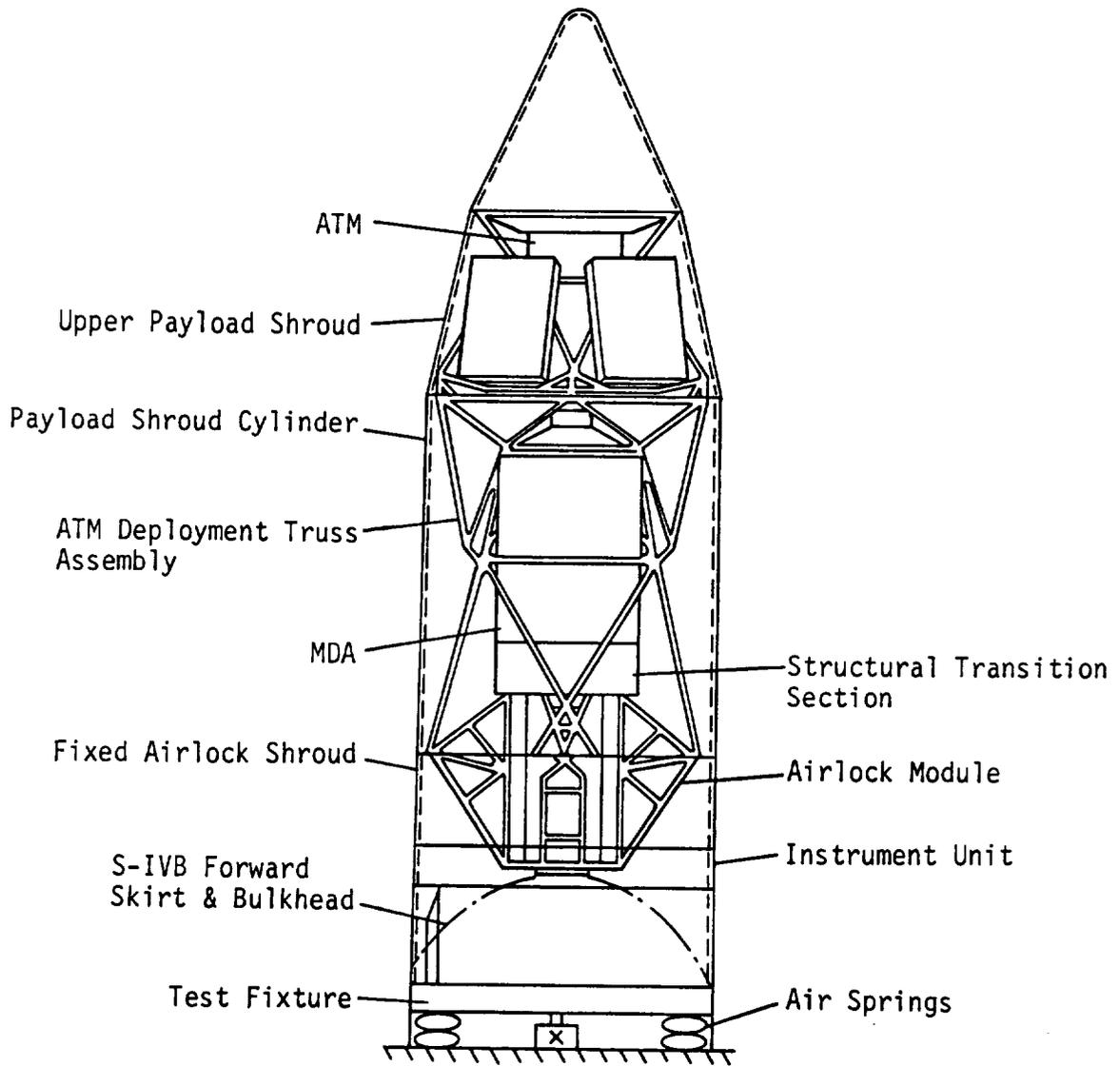


Figure III.C-2 Payload Assembly Vibration Test Configurations

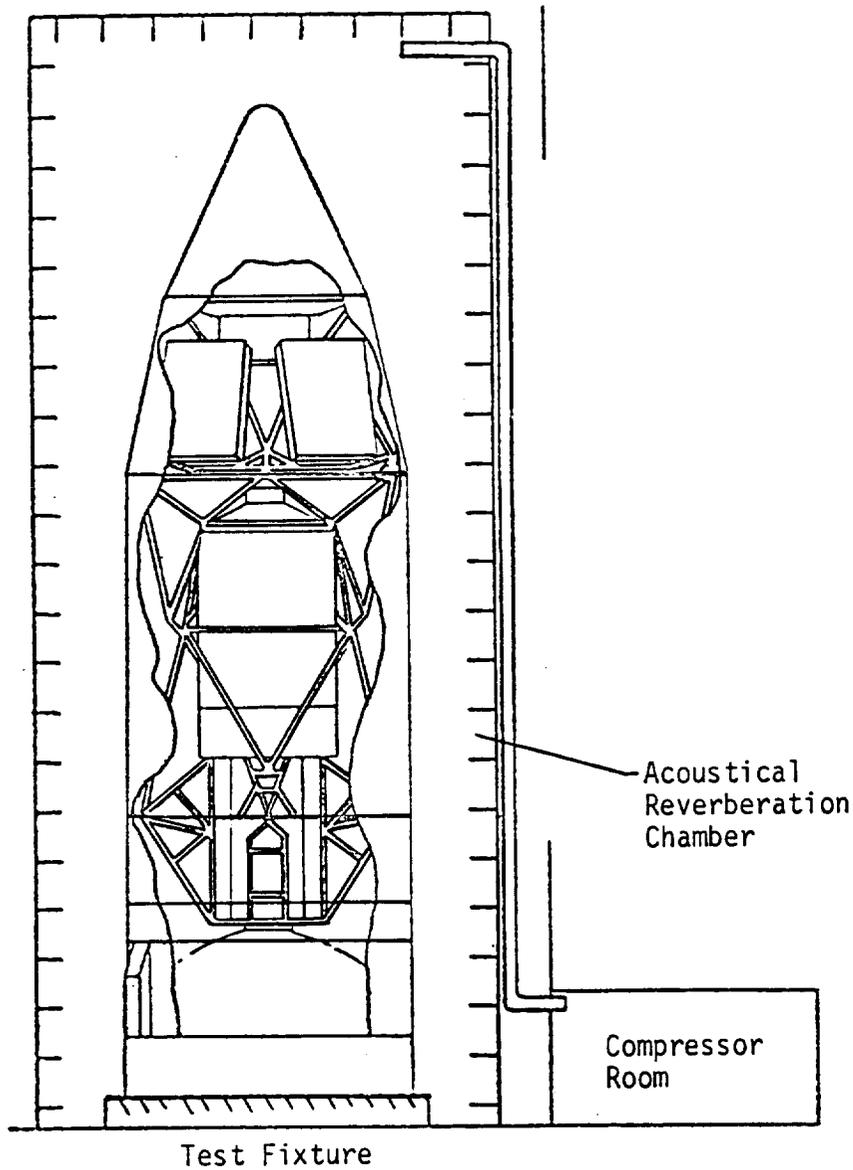


Figure III.C-3 Payload Assembly Acoustic Test Configuration

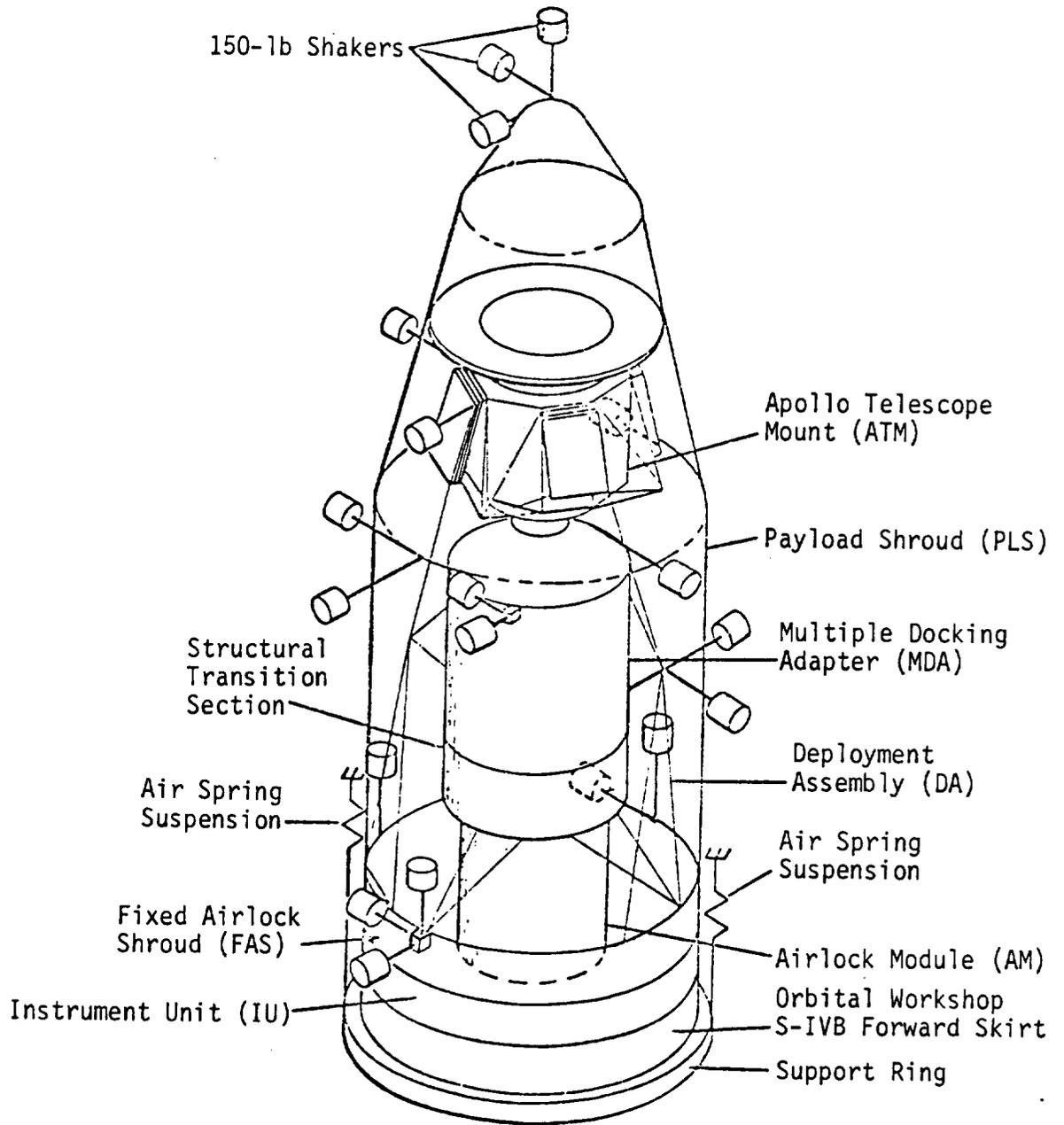


Figure III.C-4 Modal Survey Launch Configuration

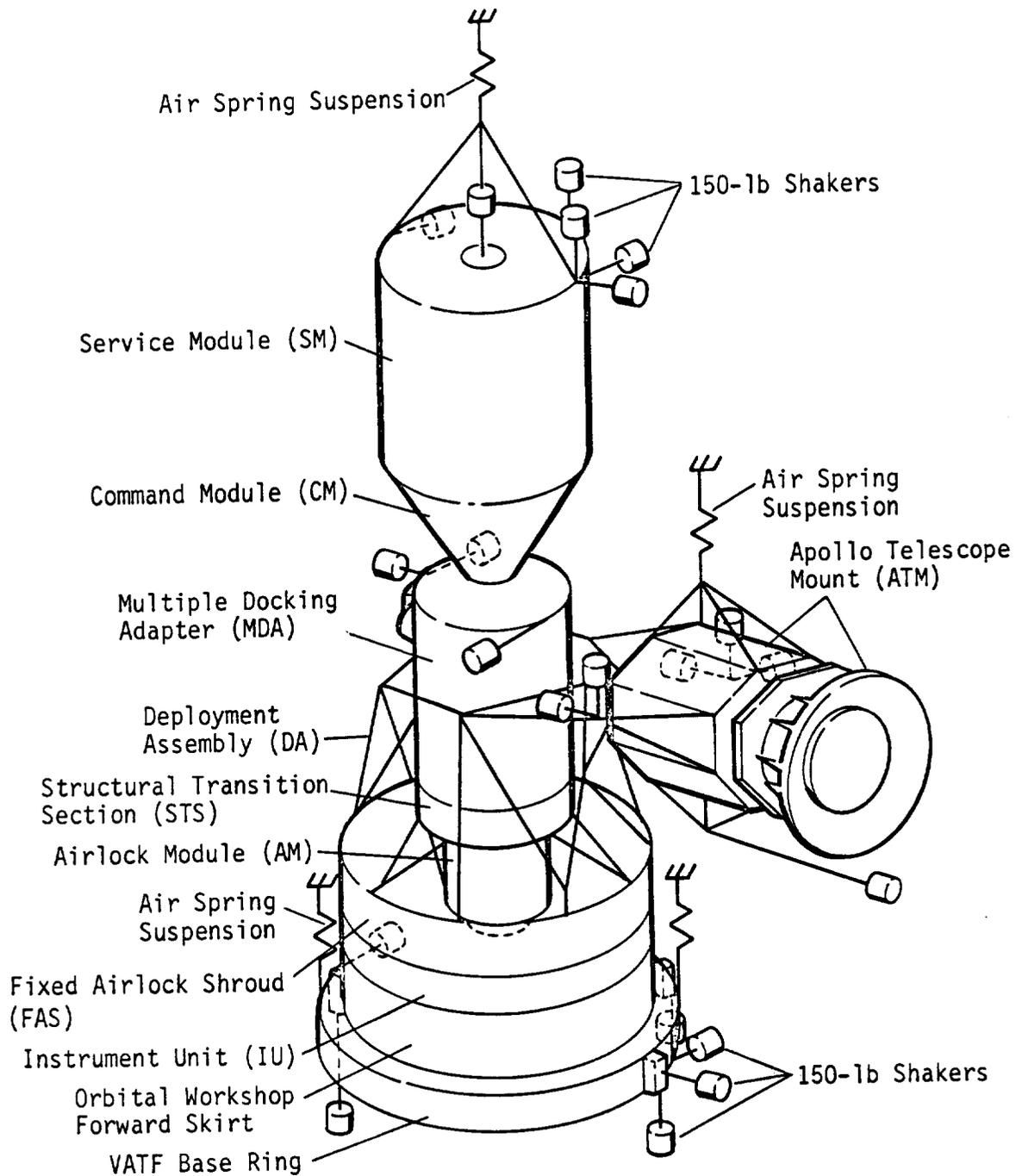


Figure III.C-5 Modal Survey Orbital Configuration

(3) Test Results. Launch and orbital configuration correlation analysis exposed modeling errors that were corrected. In addition, there were structural differences between the test and flight hardware that were corrected. Detail test results are contained in MMC Reports ED-2002-1494 and ED-2002-1546 for launch configuration, and ED-2002-1522 and ED-2002-1551 for orbital configuration.

c. OWS Vibroacoustic Test

(1) Test Location. JSC

(2) Test Objective

- Verify acoustically induced vibration design and test criteria previously selected for components and subsystems.
- Demonstrate structural integrity of bracketry and secondary structure exposed to launch acoustic and vibration environments and transient loads during staging.
- Verify analytical models used for dynamic load analyses.

The following test conditions were imposed on the hardware:

- Acoustics
 - Liftoff environment
 - Boost environment
- Low frequency vibration

(3) Test Results. No failures of basic tank structure or component attachments occurred. Sufficient data were obtained to verify or revise the dynamic design and test criteria for tank-mounted components, and to verify analytical dynamic models used to calculate dynamic loads for the OWS during launch, boost, and staging events.

Detail test results are contained in MDAC-W Report MDCG2445, dated October 1971.

d. ATM Vibration Unit Vibration Test

(1) Test Location. MSFC

(2) Test Objective

- Provide data that will be coupled with dynamic analyses to evaluate the ATM structural math models.

- Investigate the effects of complex localized vibration response induced through the ATM primary structure.

(3) Test Results. The excessive canister lateral response to low frequency longitudinal (flight axis) vibrations that occurred was corrected by revising the SIC engine cutoff sequence. This was confirmed during the Payload Assembly vibroacoustic test program.

e. ATM Prototype Unit Vibration Test

(1) Test Location. MSFC

(2) Test Objectives.

- Further verify analysis and criteria assumptions.
- Determine the effects of local vibration response induced through the ATM primary structure, components, and experiments.
- Verify ATM integrity after being subjected to vibration sources (module level qualification).

(3) Test Results. Tests completed with no significant problems. Detail test results are contained in MSFC Report S&E-ASTN-ADV (72-69) dated July 1972.

f. AM Static Load Test

(1) Test Location. MSFC

(2) Test Objectives. To demonstrate the structural capability of the combined AM/MDA vehicle and their interfaces to sustain ultimate loads associated with the critical design conditions. Test conditions included:

- Internal pressurization and leakage
- Critical liftoff conditions
- Maximum acceleration conditions

(3) Test Results. The testing on the AM Structural Test Article was successful and supplemental strength analysis verified the structural adequacy of the flight article. Test results are contained in MSFC Report IN-ASTN-TMS-71-7, dated May 1971.

g. MDA Static Load Test

(1) Test Location. MSFC

(2) Test Objectives. To verify structural integrity of the MDA structure to the critical loadings encountered in boost, flight, and docking/latching. Tests were also used to verify analytical techniques used to predict stress levels and deflections. Test conditions included:

- Local loading conditions (3 tests)
- Combinations of pressure and docking loads (6 tests)

(3) Test Results. The MDA Static Test Article verified the structural integrity of the MDA shell while subjected to the critical loading conditions. Test results are contained in MMC Report ED-2002-1264, dated May 1971.

h. OWS Static Load Test

(1) Test Location. MSFC

(2) Test Objectives. To verify the structural integrity of the S-IVB LH₂ tank for all OWS modifications for on-pad and flight conditions. Test conditions included:

- Ground wind loadings with side access panel installed and removed.
- Maximum vehicle loadings during launch and ascent.
- Maximum design differential pressure.

(3) Test Results. All test requirements were successfully met; no failures or detrimental yielding of tank structure occurred.

i. ATM Rack Static Load Test

(1) Test Location. MSFC

(2) Test Objectives

- To verify the structural integrity of the ATM rack structure for the ATM mission.
- To determine deflections at the maximum loading conditions and to determine the amount of permanent set (after removal of loads) at mounting points of various instruments for which very accurate alignment is imperative.
- To verify the analytical methods used to predict stress levels and deflections.

(3) Test Results. The test was completed satisfactorily with no anomalies. Test results are contained in MSFC Report 50M02485, dated 1 September 1972.

j. ATM Spar and Canister Static Load Test

(1) Test Location. MSFC

(2) Test Objectives

- To verify the structural integrity of the spar and the spar/canister assembly.
- To determine deflections and stresses under maximum loading conditions, and the amount of permanent set, if any, after removing loads.
- To verify analytical methods used to predict stress levels and deflections.

(3) Test Results. The test was completed satisfactorily with no anomalies. Test results are contained in MSFC Report 50M02490, dated 1 September 1972.

k. Payload Shroud Jettison Test at Altitude

(1) Test Location. Plum Brook

(2) Test Objectives.

- Verify structural integrity due to separation loads and separation dynamics.
- Verify noncontaminating design.

(3) Test Results. Three full-scale separation tests were accomplished at the Plum Brook Altitude Chamber. Minor problems, encountered during the first two tests, were corrected and the separation system and noncontamination design were verified.

1. ATM TSU Thermal Vacuum Test

(1) Test Location. JSC

(2) Test Objectives

- Verification of thermal design and operation of the ATM when exposed to maximum and minimum thermal vacuum environmental conditions.
- Collection of test data for verification of the analytical techniques used to construct the ATM thermal models.

- Determination of any significant thermal problems that could adversely affect the success of the ATM program in subsequent testing and flight.
- Development of shipping, handling, and testing techniques for prototype and flight hardware.

(3) Test Results. Testing resulted in thermal redesign of several components to provide the required temperature control. Redesigns were subsequently verified on the ATM Prototype and Flight Article thermal vacuum tests. Detail test results are contained in Report ED-2002-1174-1 dated January 1971.

m. ATM Prototype Thermal Vacuum Test

(1) Test Location. JSC

(2) Test Objectives

- Verification of proper operation of the ATM systems in a simulated orbital thermal vacuum environment.
- Determination of any significant thermal problems that could adversely affect the success of the ATM program in subsequent testing and flight.
- Provide test data for verification of the analytical techniques used to construct the ATM thermal math models.

(3) Test Results. Prototype thermal vacuum testing verified "fixes" resulting from TSU testing, and in some additional redesign for the flight ATM. These changes were subsequently verified in the flight ATM thermal vacuum testing. Detail test results are contained in Report ED-2002-1434-2 dated April 1972.

n. Cluster Electrical Power System Breadboard

(1) Test Location. MSFC

(2) Test Objectives. The overall purpose of this testing was to verify proper operation of the Cluster EPS systems in their parallel modes of operation before mating of the actual flight systems. To accomplish this purpose, a Skylab Cluster Power Simulator was developed at MSFC. The specific primary objectives of the testing were to:

- Demonstrate the capability of the AM and ATM power systems to operate in parallel, and to verify stable operation of the two systems when subjected to the flight power profile.

- Demonstrate that flight circuit wiring is adequate for proper load sharing by the power systems.
- Analyze the effects of the single-point-ground system concept with the cluster power systems in its various configurations.
- Demonstrate and analyze power system failures and contingency modes of operation.
- Determine short-term and long-term effects of simulated orbital operation on the systems and particularly on their batteries.

(3) Test Results. Testing on the EPS breadboard was very successful. Testing was initiated early enough so that any problems could have been solved without affecting launch schedules. However, no problems were encountered with the parallel operations of the Cluster EPS systems. The testing verified the compatibility of the AM and ATM power systems and their capability to interface with the simulated CSM power system. Flight procedures associated with the EPS systems were verified on the breadboard. Contingency procedures to overcome simulated system malfunctions were also verified by breadboard testing. Detail test results are contained in MSFC Report TMX-64818 dated June 1974.

o. Attitude and Pointing Control System Integration Tests

(1) Test Location. MSFC

(2) Test Objectives

- To evaluate overall system performance with primary emphasis on system stability, pointing accuracy, and dynamic response.
- To verify system hardware compatibility.
- To verify flight software for the workshop computer.

Testing was performed under ambient lab conditions starting with CMG/TACS and EPC buildup, CMG/TACS and EPC subsystems simulation, and progressed into a complete integrated APCS control system simulation. The major tests included:

- CMG/TACS Subsystem Tests. Establish the system capability to provide cluster attitude control during various flight modes.
- EPC Subsystem Tests. Determine the system capability to provide accurate pointing and control during the experiment pointing operational mode.

- CMG and EPC Subsystems Integration Tests. Verify operation readiness of the combined subsystems and establish overall system capability to perform mission requirements.
- APCS/C&D Integration Tests. To test applicable C&D functions during a simulation orbital mission.

(3) Test Results. Three independent simulators were used in performing hardware simulation and software verification. The System 360 Model 75, located at IBM in Huntsville, is an all digital software simulator that modeled both the vehicle and the ATMDC. The System 360 Model 44, located at IBM in Huntsville, incorporated a flight-type ATMDC with software models of the WCIU and the vehicle. The Hardware Simulation Laboratory (HSL), located at MSFC, is an all-hardware simulation with the exception of software equations for vehicle body dynamics and software simulation of the OWS TACS. The HSL also had the capability of substituting software models for all sensors and actuators with the exception of the ATMDC. The functions performed by the simulators were Software Verification, System Integration, and Dynamic Responses. These functions were investigated for the following operational periods:

- Activation periods investigated and verified were ATM deployment and CMG/TACS activation.
- Normal periods investigated and verified were rendezvous and docking, maneuvers, experiment operation, navigation, timing, and attitude control.
- Contingency situations investigated and evaluated included redundancy management (CMG, rate gyro, and acquisition) and sun sensor, ATMDC self test and switchover, 8K program, and random reacquisition.

Detail test results are contained in MSFC Report 50M78002, dated January 1973.

p. Audio Center and Voice System Compatibility Test

(1) Test Location. MDAC-E

(2) Test Objectives

- To verify proper operation of the SL communication system when married to the CSM (simulated) audio centers.
- To verify proper transmission and reception of voice using the (simulated) CSM S-Band transmitter.

(3) Test Results. The SL communications system worked well with the audio centers and test results were nominal.

Transmission and reception were adequate for communication purposes. Details can be found in the MDAC-E Report No. 061-063.19 dated 15 March 1972.

q. Audio System/Caution and Warning System Compatibility Test

(1) Test Location. MDAC-E

(2) Test Objectives

- To verify operating compatibility between the (full up) audio system and the C&W system.
- To verify proper isolation exists between redundant systems.
- To verify emergency warning signals are adequately isolated from other audio signals.

(3) Test Results. Test results were nominal in all areas so compatibility was verified and isolation was deemed adequate. Details can be found in MDAC-E Report No. 061-063.18 dated 1 April 1972.

r. STU/STDN Compatibility Tests

(1) Test Location. MDAC-E

(2) Test Objectives

- To evaluate compatibility between a typical STDN ground station and a Skylab test unit that simulated the cluster I&C system.
- To support real-time AM/MDA testing during the planned test flow.
- To provide real-time mission support as an I&C breadboard.

(3) Test Results. Tests in all modes proved to be successful. Incompatibilities were not detected and both local and mission support testing performed as expected. A final test report was not issued since CCP 171 did not require a report.

s. EREP Integrated Systems Bench Test

(1) Test Location. MMC

(2) Test Objectives

- Verify by subsystem and system the compatibility of the EREP sensors and experiment support equipment.
- Refine test methods and test data analysis techniques before starting module level testing.

(3) Test Results. Based on the analysis of the EREP Systems Bench Test tapes and the resultant hardware corrections made during the test, it was concluded that the electrical, functional, and data interfaces for each experiment were verified. The hardware corrections made and software developed as a result of the bench test simplified future testing and test data analysis. The analysis of the bench test data also verified the value of the bench tests as a necessary step in establishing confidence in the EREP System. Detail test results are contained in JSC Report MSC-03173, dated 31 January 1972.

t. Skylab Medical Experiments Altitude Test (SMEAT)

(1) Test Location. JSC

(2) Test Objectives. The objective of the SMEAT was to provide a nearly full-scale simulation of a 56-day Skylab mission. Detail objectives were:

- Obtain and evaluate baseline medical data for up to 56 days for those medical experiments that might be affected by the Skylab environment (except weightlessness).
- Evaluate selected experiments hardware, systems, and ancillary equipment.
- Evaluate data reduction and data handling procedures in a mission duration time frame (all mission constraints imposed).
- Evaluate preflight and postflight medical support operations, procedures, and equipment.
- Evaluate medical inflight experiment operating procedures and crew checklists.
- Train Skylab medical operations team for participation during the flight.

(3) Test Results. The SMEAT Program lasted for the full scheduled 56-day period. No major problems were encountered that threatened its success. A number of problems did develop that required

correction before launch of Skylab. Detail test results are contained in JSC Report NASA TMX-58115, dated October 1973.

u. Biomedical System Integrated Systems Test

(1) Test Location. MSFC

(2) Test Objectives. The Biomedical System Integrated Test conducted at MSFC was the first attempt at operating the various elements of the Biomed system together. Design Verification Test Units (DVTUs) were used for the test. Specific test objectives were:

- To verify component interfaces within each experiment and interfaces between the Experiment Support System (ESS) and its modules (e.g., ESS to Blood Pressure Measuring System Module).
- To prove the electrical and mechanical interfaces between experiments M092, M093, and M171; the ESS; and the Experiment Checkout Equipment (ECE) are compatible.
- To verify the functional operation and electromagnetic compatibility of each experiment.
- To verify that the experiments are safe to operate with human test subjects and demonstrate system capability to provide required physiological data.
- To operate the experiments as an integrated system to evaluate mission timelines and to demonstrate design performance and compatibility.

(3) Test Results. The testing pointed out many problems that were subsequently eliminated or reduced by redesign of the hardware. These redesigns were verified on the DVTU integrated testing, and during the integrated testing using the flight hardware. A final test report was not issued for this test.

v. Crew Systems Testing.

(1) Test Location. Module Contractors, MSFC, JSC

(2) Test Objectives. Crew systems testing is defined as all One-G, Zero-G, and neutral buoyancy tests. The objectives of this testing were to:

- Assist designer in verifying adequacy of hardware design,
- Develop procedures,

- Prove compatibility of man and machine relationships,
- Evaluate astronaut assigned tasks, and
- Determine proper sequence for task performance.

(3) Test Results. The AM, MDA, OWS, ATM, and experiments all performed extensive testing in the crew systems area. This testing is discussed in some detail in Section II of this report.

2. Qualification Test Program

a. General. Qualification tests were required to be performed on all flight hardware in Criticality 1 category to verify that Skylab production hardware met the design specification and long-life requirements necessary for operational suitability. Flight hardware components in Criticality 2 and 3 categories were qualified at the highest practical level by one or a combination of the following methods:

- Test
- Similarity
- High assembly
- Prior test, flight, or usage experience
- Analysis
- Requalification

Refer to Table III.C-1 for a definition of Criticality Categories.

Table III.C-1. Flight Hardware Criticality Category

CATEGORY	POTENTIAL EFFECT OF FAILURE
1	Loss of life or crewmember(s) (ground or flight)
1S	Applies to Safety and Hazard Monitoring System. When required to function because of failure in the related primary operational system(s), potential effect of failure is loss of, or risk to, life of crewmember(s).
2A	Immediate mission flight termination or unscheduled termination at the next planned earth landing area. (For SL, includes loss of primary mission objectives).
2B	Launch scrub.
3	Launch delay (for SL, includes loss of secondary mission objective).
3A	Degradation of primary mission objectives resulting from a component failure that impacts two or more related experiments.

b. Program Definition. The component qualification test program was established and defined by the applicable module Qualification Test Plan:

AM F767
MDA ED-2002-1005 Volume II
OWS DAC-56697
ATM 50M02408

The plans defined the requirements for qualification by test for all CFE components, and a system for verification of qualification certification for GFE components.

All components were analyzed and qualification testing performed when the analysis indicated that insufficient information was available to verify the design and performance requirements. This testing was performed on flight-type hardware to formally demonstrate that the developed design would perform according to specification under conditions that simulated the most severe mission conditions predicted plus a margin. All qualification test units were subjected to and successfully passed all performance/environmental acceptance test requirements before entering the qualification test program.

c. Testing. The testing was conducted in accordance with approved test procedures that implemented the Qualification Test Plan. All performance environmental and testing had surveillance by NASA representatives. MSFC program offices had final approval for the final test reports. Inhouse MSFC review of the test procedures and test reports was provided by S&E-ASTR, ASTN, and QUAL Laboratories.

d. Program Reviews. Acceptability reviews were held by NASA teams to provide an in-depth review of each of the contractors components. For those components supplied by the government an internal review was held by S&E-QUAL personnel with inputs provided to the applicable program office. As an added management tool, beginning approximately one and one-half years before launch, a qualification test status board, that was updated weekly, was maintained in the Skylab Management Center.

e. Certification. Qualification certification was obtained on all components. This certification was the final requirement of the component qualification program.

D. Flight Hardware Verification

1. General. This section discusses in general terms the module verification program at the contractor facilities. No attempt has been made to include the Crew Compartment Fit and Functional (C²F²) tests in this section. These are covered in detail in Section II, SWS Systems, of this report. Reference is made to the module reports if additional information is required. The significant open items in the test program

at the time of shipment of the hardware to KSC are included. Figure III.D-1 identifies the general span time of the flight hardware module and integrated test program.

2. OWS Test Program. The OWS module went through a series of subsystem and system tests and experiment integration tests at Huntington Beach to verify system operation at the module level. All Systems Tests were then accomplished to assure that all equipment and subsystems satisfy design and mission objectives when operated independently and collectively, and to determine if any undesirable interactions existed between the flight OWS and/or experiments.

Details of the OWS module test program are contained in MSFC Report TMX-64813, dated May 1974.

3. ATM Test Program. The ATM module went through a series of systems and experiment tests at MSFC to verify system performance before initiation of the ATM All Systems Test. The All Systems Test involved the complete ATM, which was powered in a launch-orbit sequence, and the system operated to simulate an actual mission. This test functionally verified the systems operational compatibility. Two All Systems Tests were performed:

- (1) Primarily concerned with EMC verification;
- (2) Verified the integrity of the ATM after removal of the EMC breakout.

The ATM was then subjected to vibration tests to provide assurance the flight system would withstand mission performance following the boost phase of the vehicle flight.

Following the vibration test, the ATM was shipped to JSC for post-vibration alignment verification and thermal vacuum testing. There a series of functional tests were performed on the ATM in a thermal vacuum environment to verify mission operation under a simulated space condition.

For details of the ATM module test program, refer to MSFC Report TMX-64811, dated June 1974.

4. PS Test Program. The PS module went through electrical systems tests and mechanical fit checks at Huntington Beach to verify systems acceptance. After weight and balance checks, the PS was stored until the hardware was required at KSC.

There were no significant open items in the PS test program at the time of shipment to KSC.

5. MDA Test Program. The MDA module went through a series of subsystem and system tests and experiment integration tests at Denver and

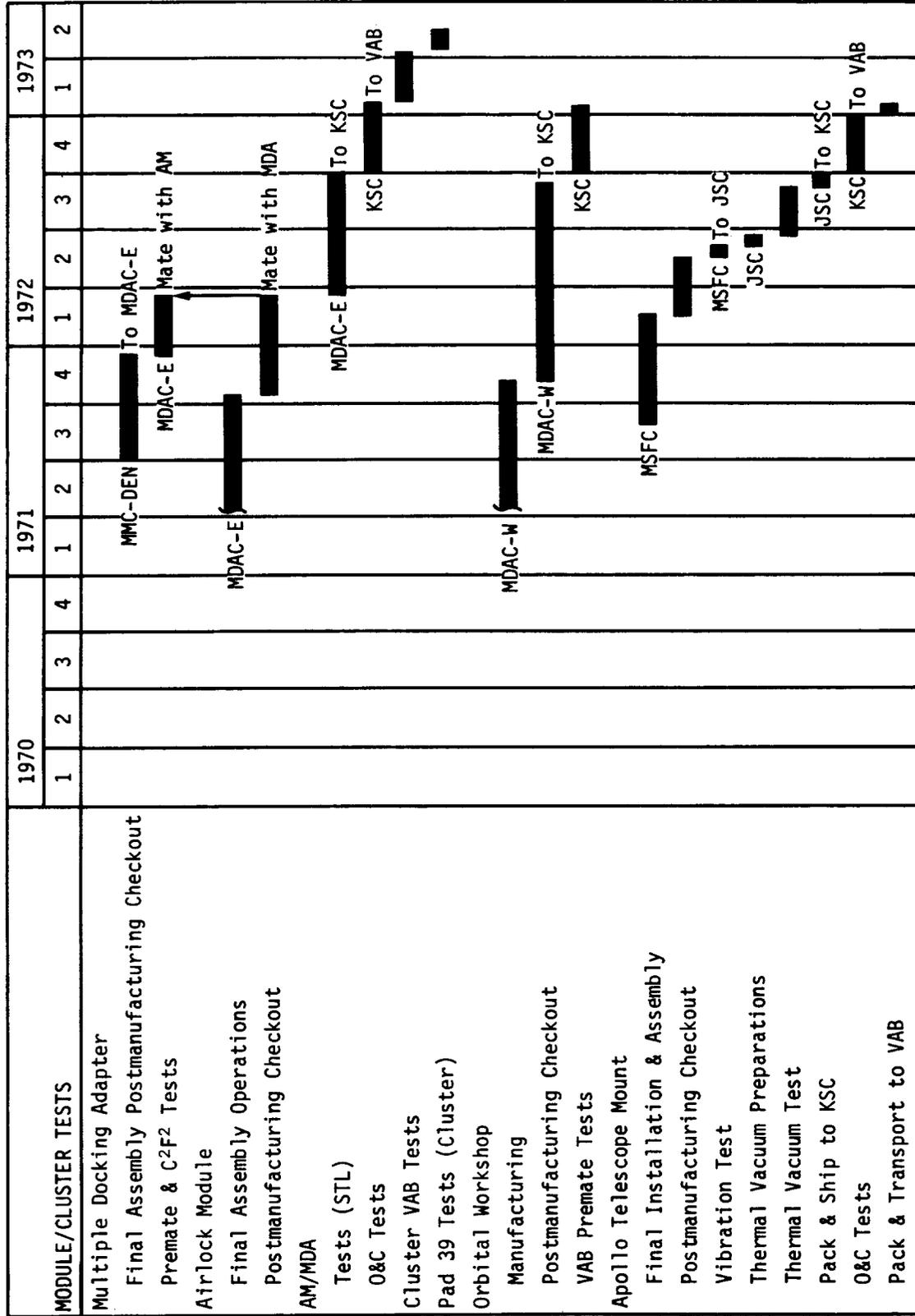


Figure III.D-1 Skylab Flight Hardware Test Program

St. Louis to verify system operation at the module level. The AM and CSM functional interfaces were simulated during this testing. No attempt was made to accomplish an all systems type test on the MDA alone. This testing was performed during the AM/MDA Simulated Flight and Altitude tests at St. Louis.

Details of the MDA module test program are contained in MSFC report TMX-64812, dated April 1974.

For significant open items in the MDA test program at the time of shipment to KSC, refer to Section III.D.7.

6. AM Test Program. The AM module went through a series of subsystem and system tests at St. Louis to verify systems performance at the module level. MDA, OWS, ATM, and CSM simulators were used during these tests. An all systems test or integrated systems test was accomplished after the AM and MDA were mated.

Details of the AM module test program are contained in MSFC Report TMX-64810, dated May 1974.

7. AM/MDA Test Program. Upon completion of the initial AM testing, the MDA was shipped from the Martin Marietta Denver facility to MDAC-E by Super Guppy aircraft. The MDA was mated with the AM twice, the first mate being for the purpose of mechanical interface and clearance checks. During this mate, the AM/MDA was mated to the FAS. The ATM DA was then assembled and the MDA was then permanently mated to the AM.

The MDA was delivered to MDAC-E with several pieces of hardware either not installed and/or tested. The principal components were the five EREP and the ATM C&D console. This hardware was installed and tested at MDAC-E before delivery of the AM/MDA to the launch site.

Testing during this period included the systems assurance test of each system of the mated AM/MDA; C²F² performance of a simulated flight test wherein systems were operated in the expected flight sequences; the Manned Altitude Chamber Test; completion of EREP and ATM C&D panel installation and test; and additional C²F² and simulated flight tests to validate the late hardware. During this period, the Astronauts participated principally in the C²F² simulated flight test, and altitude chamber tests. The crewmen for the altitude chamber test consisted of the prime crew for SL-2. The mated AM/MDA, the FAS, and the DA were then prepared for individual delivery to KSC by means of Super Guppy aircraft.

Details of the MDA and AM test programs are contained in MSFC reports TMX-64812, dated April 1974, and TMX-64810, dated May 1974, respectively.

Significant open items in the AM/MDA test program at the time of shipment to KSC were retest S190 window latching mechanism, ILCA lighting test, TV system test, C²F² testing, and EREP sensor retests.

E. KSC Test Program

1. General. At KSC, the prelaunch test program consisted of module reverification, testing to demonstrate each module ready for multimodule testing, multimodule interface verification, end-to-end system test, and a mission simulation test. This verification program culminated in countdown demonstration, and the final countdown with a successful launch on May 14, 1973.

During the prelaunch test program, several first time verifications were made, i.e., electrical bonding resistance, AM/ATM power systems paralleling, single-point-ground transfer between CSM and AM, AM/MDA audio with CSM audio center, OWS measurements using the AM PCM system, etc. These first time verifications were conducted without major incident. It was MSFC philosophy that the first time mating and testing at KSC was an essential part of design verification.

This report will discuss the multimodule interface verification, end-to-end system test, and the mission simulation test.

2. AM/MDA-CSM Electrical Interface and Docking Simulated Mission Test. On December 4, preparations were initiated for the AM/MDA-CSM Electrical Interface and Docked Simulated Mission Tests. The tests functionally verified the AM/MDA-CSM electrical interface compatibility of the power, C&W, TV and communications systems, and the atmosphere interchanging duct, and determined the operational compatibility of the vehicles during a mission simulation. The test also included the actual docking of the AM/MDA-CSM; tests during docking that verified the mechanical compatibility of the AM/MDA, docking target alignment, tunnel leakage rates, and the electrical bonding characteristics of the mated AM/MDA-CSM. The test was successfully completed on December 18 and the modules undocked on December 20.

Several significant first time verifications were successfully conducted during the AM/MDA-CSM test. They were:

- Probe-retract (compressive manual load),
- Probe capture latch(es) engagement/release and interface fit tolerance,
- Probe droge removal/installation and stowage capability,
- Docking ring latch(es) verification,
- CSM-AM/MDA transfer tunnel pneumatic verification,
- Air interchange duct and electrical connector mate/demate,
- Electrical bonding resistance CSM-AM/MDA,
- Docking target alignment,
- C&W interface CSM-AM/MDA-fire sensor and power bus,
- Intermodule voltages and commands CSM-AM/MDA,
- SWS single-point-ground bi-directional transfer between CSM and AM,
- AM/MDA TV transmission to STDN via CSM S-band transmission,

- AM/MDA audio with CSM audio center,
- AM/MDA audio to STDN via CSM S-band transmitter, and
- AM DCS control of CSM S-band OMNI antenna.

3. AM/MDA/OWS Leak Test. The AM/MDA/OWS Leak Test, which ascertained the leakage rates of the various systems aboard the AM, MDA and OWS and verified the integrity of the interface, was successfully completed February 11, 1973. First time verification of the AM/OWS interface seal leakage and leak and flow of fluid lines were successfully completed during this test.

4. SWS End-to-End Systems Test and Experiment Test. The SWS End-to-End Systems Test and Experiment Test was the first time the flight systems were operated end-to-end. Portions of the SWS End-to-End Systems Test and Experiments Test began on February 8, 1973. Problems with the refrigeration subsystem GSE were the pacing items during this test. A GSE quick disconnect was leaking and required replacing. The Coolanol had an unexplained yellow color; however, after an evaluation by MSFC it was decided to use the Coolanol as-is. The SWS End-to-End Systems Test and Experiments Test continued through February 25, 1973, testing various control circuits, waste management, C&W system, lights, all ordnance circuits, I&C systems, as well as EREP and certain experiments checkout.

Significant first time verification successfully conducted during this test were:

- Intermodule voltages and commands,
- Bus characteristics during maximum power transfer and largest anticipated mission power sharing between modules,
- AM and ATM power system paralleling,
- Payload shroud jettison ordnance circuitry,
- Entire SWS TV system connected together (except CSM),
- OWS audio system using AM audio load compensator,
- OWS measurements using the AM PCM and tape recorders for transmission,
- OWS digital display unit being used by the AM timing reference system,
- AM DCS sending commands to the ATM,
- AM sending commands to the OWS, and
- OWS control of aft AM heat exchangers.

5. Interface Test. In parallel with the SWS End-to-End Systems Test and Experiments Test, the IU Interface Test was conducted on February 23, 1973. This test verified the OWS switch selector interfaces and ensured that other systems operating during this test did not transmit false commands to the switch selector. First time verifications during this test included:

- OWS switch selectors receiving commands from the IU, and
- OWS switch selectors stimulating AM/ATM functions.

6. IU/ATM/OWS TACS Test. The IU/ATM/OWS TACS Test started March 6, 1973 to verify the capability of the IU and ATM to provide necessary signals to the TACS and to accomplish the required attitude control functions, and to verify the proper TACS response to these controls. The TACS test was completed on March 9, 1973 and all spacecraft modules went into a pre-FRT inspection and work period. An open-item review revealed a large number of constraints to the start of the SV OAT and SWS Mission Simulation/FRT. During the next ten day period, maximum effort was put forth to work off all constraints.

7. Space Vehicle Overall Test and the SWS Mission Simulation/Flight Readiness Test. The Space Vehicle Overall Test and the SWS Mission Simulation Flight Readiness Test was successfully completed on March 25, 1973. This test verified the IU/SWS interface compatibility in the flight mode, demonstrated electromagnetic compatibility between the individual SWS systems and between SWS system and associated experiments, and accomplished an open-loop VHF ranging test to the CSM on the adjacent pad. Mission simulation activity included spacecraft activation, orbital operations, and deactivation. This sequence of tests was based on mission profile sequencing, but did not attempt to duplicate nor verify the actual profile. AM/MDA flight batteries were used for the first time during this test.

8. Flight Systems Redundancy Test/Software Integration Test. The last multimodule test before movement to the pad was the Flight Systems Redundancy Test/Software Integration Test which was successfully completed on March 28, 1973. This test verified ATM/LV interface in the guidance system, demonstrated the compatibility of the space vehicle with the command network and the suitability of the Operational Handbooks for the conduct of the mission, and verified operation of the backup command modes.

9. Intercenter KSC Test Review. An intercenter KSC Test Review was held during the week of March 26-30, 1973. Results of this review assisted in determining the flight readiness of the SWS systems, and readiness to roll-out from the VAB to the pad. Discrepancies were documented for review by the Review Pre-Board on March 30, 1973. All were disposed of by the Pre-Board except for two problems that required action by the Review Board on April 2-3, 1973:

- DC/DC converter no. 1 five volt output dropped from 5.022 volts (nominal) to 4.64 volts for approximately 1.2 seconds, and was out of regulation for approximately 3.0 seconds.
- Video output of flight TV camera (S/N 3002) degraded during KS-0009 test. (Problem repeated off module, video output quality unacceptable. Problem was isolated to EMI internal to camera).

Neither problem impacted the roll-out of the pad and both problems were resolved before liftoff.

10. Countdown Demonstration Test. SL-1 was transferred to Pad A on April 16, 1973 with the only test planned to be the Countdown Demonstration Test (CDDT). SL-1 CDDT started at T-123 hours at 1900 EDT on April 26, 1973. Final stowage of the ATM cameras and film in the MDA stowage locker and flight closeout of the MDA was completed on April 27, 1973. Final closeout of the AM/MDA was completed on May 1, 1973 and the EVA hatch was secured for flight. The space vehicle successfully completed CDDT Wet at 1330 EDT on May 2, 1973 with no anomalies encountered.

11. Lightning Retest. Launch countdown began of 0200 EDT on May 9, 1973. A small amount of water fell in the ATM area during a thunderstorm on May 9, but affected areas were temporarily covered. High winds prevented further weather-proofing of the payload shroud nose cap until May 10, 1973. The Mobile Launcher 2 lightning mast was struck by lightning at 1257 EDT on May 9, 1973. The following lightning retest actions were taken to ensure the integrity of the space vehicle systems.

a. A full retest was performed on the launch vehicle - part under the Lightning Retest Plan and the remainder during the Launch Countdown.

b. An abbreviated retest was conducted on the spacecraft (SWS) that included a memory check of the ATM computer, a functional test of the PCG, a DCS functional check, and a TM functional test. No anomalies attributed to the lightning were noted.

F. Verification Documentation

Figure III.F-1 depicts the top level test planning and requirements documentation developed and implemented during the Skylab verification program. The Apollo Applications Requirements Document, NHB8080.3, was used as a guideline in establishing the Skylab Payload Verification Program.

The content, format, and number of documents required to identify KSC requirements was established by intercenter management agreement and was in general accordance with SLPD No. 26.

G. Conclusions and Recommendations

The following discussion presents conclusions and recommendations regarding the Integrated Test Program. No attempt is made to present module level recommendations as these are included in the individual module reports. Recommendations presented should be considered as candidates for future programs that may involve hardware and test programs approaching the sophistication of Skylab.

1. Test Planning

a. Conclusions. A Master Verification Plan was prepared by S&E-CSE to interpret the Cluster system requirements into program verification plans. It provided management visibility of the overall test program and a means by which the affected elements of Science and Engineering could assure that system verification activities were adequate and responsive to program requirements.

b. Recommendations. A top-level verification plan should be prepared early in the program and updated periodically to provide management visibility of the overall verification program. The plan should be used as the single source document for establishing and evaluating lower level test plans against overall verification objectives. The updates should be continued until the flight hardware/module test program has started.

2. Test Requirements

a. Conclusions. Formal TCRSDs were prepared for all module acceptance testing (except for AM testing at St. Louis), and for all module and integrated testing at KSC. The TCRSDs included experiment checkout requirements for on-module testing.

TCRSDs were the basis for preparation of the procedures used during acceptance testing of the modules and for the KSC test activities. These documents were invaluable in establishing program verification compliance.

b. Recommendations. TCRSDs should be prepared for all module level acceptance testing and for any multimodule or integrated systems testing. The formation of Cluster systems test requirements review teams proved to be a successful approach and should be used for future programs.

For the development of experiment integration test requirements, the method used for the Skylab experiments should be considered. A series of PATRSs meetings were held to review preliminary experiment test requirements. The attendees included the Module Contractor; Experiment Developer; Experiment Development Center; and the Module, GSE, and Experiment Projects offices from MSFC. The output of the meetings was a coordinated Experiment Integration Test Requirements and Specification (EITRS) document that eventually was incorporated into the applicable Module TCRSD.

3. Test Procedures

a. Conclusions. The procedures used for module checkout at KSC were, for the most part, unique to the KSC operations (with the exception of the ATM procedures). It would lead to a more efficient operation if standardized test procedures for manufacturing acceptance through launch could be developed.

Plans for crew participation in factory checkout or other tests should be made in time for procedures to be developed which are acceptable for crew use. This required a learning period for an organization not experienced in writing such procedures.

b. Recommendations. Develop and use launch site procedures as much as possible for factory checkout. This will require early participation by launch and operations personnel in planning requirements.

Identify crew participation requirements well in advance so the proper attention can be given to the preparation of crew-oriented procedures.

4. Test Teams

a. Conclusions. The program benefitted greatly from the "traveling test team" concept. Each module was followed by a dedicated NASA-industry test team from factory checkout through launch. The readily available experience thus accumulated was invaluable in troubleshooting and implementing changes.

b. Recommendations. Use a similar concept for future programs.

5. Test Scheduling

a. Conclusions. The KSC planned test schedule was overly optimistic for a test program of the magnitude of Skylab. There was a significant amount of first time testing that was scheduled for KSC, as well as open testing that was originally scheduled for the factory but not accomplished. The planned test schedule went from 8 hour shifts five days a week, to around-the-clock six days a week.

b. Recommendations. Ensure that a realistic test planning schedule is defined for the amount of testing that is to be accomplished at KSC.

6. Test Program Evaluation

a. Conclusions. For a program of the complexity of Skylab it is essential that the verification program be developed, controlled, and continuously evaluated on a total system basis as well as by individual module. On Skylab this was accomplished by a comprehensive system of intercenter reviews starting with the SOCAR and continuing through the DCR and the FRR.

b. Recommendations. Evaluate the verification program on a Cluster system basis as well as by individual module or experiment. Identify the major intermodule or Cluster system verification requirements (both test and analysis) early in the program, document the status with periodic updates, and ensure adequate follow-up for problem areas. The evaluation process should continue through the KSC prelaunch test

program. Intercenter reviews should be held periodically to review the status of the verification program with emphasis placed on the problem areas.

7. Mission Support Testing

a. Conclusions. The value of maintaining the module backup hardware, Cluster system breadboards/simulators, and the crew systems hardware in readiness to support the Skylab mission was evidenced by the many tests accomplished on this hardware. These tests measurably contributed solving real and contingency on-orbit problems.

b. Recommendations. Use backup hardware and functional flight type simulators for mission support testing.

8. Prototype Units

a. Conclusions. The Skylab flight hardware test program encountered many delays that could have been eliminated had there been prototype hardware available in advance of the flight hardware.

b. Recommendations. Include an all-systems prototype in the program so design, procedure, or facility problems can be identified with adequate lead time for correction. This unit can be refurbished for flight or real-time mission support.

IV. Mission Operations

SECTION IV. MISSION OPERATIONS

A. Introduction

1. Purpose. This report documents the objectives and methods used by MSFC mission operations in preparing for and supporting the Skylab mission.

2. Scope. The time frame covered is from conceptual phase AAP-1S through SL-4 splashdown and post-mission data distribution.

3. Historical Summary. To effectively support prelaunch and launch operations for which KSC had responsibility and the flight operations for which JSC was responsible, the MSFC operations task was to fine, plan, and implement engineering support capability for Skylab, while retaining support capability for Saturn V and 1B launch vehicles. Saturn support facilities existed and precedents were established for the Saturn support roles; however, a number of significant factors added other dimensions to Skylab support as follows:

- Skylab support was longer duration (months vs days);
- Simultaneous support of two launch vehicles and the OA was required;
- Science data requirement quantities and types for handling and processing were vastly expanded.

"Lessons Learned" are discussed specifically in the following sections, where applicable. In general, certain functions should have been initiated earlier in the program with other aspects of these functions receiving the emphasis; however, mission support concepts were very successful in meeting mission objectives.

a. Historical Systems Operations Analysis Summary. A MSFC operations team was located at JSC for the Saturn launch vehicles to provide Booster Systems Engineer (BSE) flight control console manning and associated staff support functions. Communications and data links at the HOSC at MSFC were maintained for engineering and management operations for the Saturn program.

The prelaunch and launch support roles for HOSC were well established with facilities and data links from KSC for systems integrated test, flight readiness test, countdown demonstration test, and countdown.

Intercenter design discipline panels were established by subsystems to provide for interchange of engineering data with operations personnel. The panel members participated in design reviews and SOCAR to ensure that operational documentation reflected actual systems designs. This allowed operations documentation to be started while design engineering problems were worked.

The rapport developed in some of these technical discipline groups during SOCAR provided impetus to a decision for MSFC support to the Skylab Missions by use of MSGs. The following groups were formed:

- Support Team for Attitude Control
- Electrical Power System
- I&C System
- Environmental Controls System
- Apollo Telescope Mount Thermal Control System
- Contamination
- Structures and Mechanical
- Crew Systems
- Apollo Telescope Mount Experiments
- Corollary Experiments

These personnel provided in-depth analysis of engineering problems in support of the JSC Mission Control Center (MCC) console positions and their Staff Support Room (SSR) activities through the FOMR. Off-line computer models at MSFC and support contractors would be used for predictions and contingency analyses, as required.

The mission management function for Skylab was provided by the FOMR, which involved both MSFC and JSC personnel.

The MSFC flight operations support team at JSC was charged with responsibility for providing console engineers and support for activation of the OA in addition to Saturn support for the unmanned SL-1 and manned SL-2, -3, and -4 Saturn BSE functions. These personnel, who had technical responsibilities for Skylab hardware, participated in training and simulations. Simulations conducted at MSFC were successful in exercising procedures, communications systems, operations support staff, and MSGs. An end-to-end data flow test was never completed, which further reduced simulation fidelity.

Future programs should provide for early simulation planning and software development, be phased to allow test and checkout of the data flow system (end-to-end), and provide time for problem solution.

Management attention was focused upon delivery and launch readiness of flight hardware, and as a result, the simulation exercises received a lower priority. Future programs should provide management emphasis, manpower, facilities (hardware and software), and adequate planning time to provide for realistic data to support the simulations.

b. Historical Data Management Summary. A data management plan was developed to establish the approach for building the data management system. Center responsibilities and roles were established for acquisition, processing, statusing, coordination, and dissemination of the many types of Skylab data.

The Program Support Requirements Document (PSRD) was the medium used for requirements levied at Headquarters level upon all NASA centers and support agencies. The requirements emphasized were those having a long lead time for sizing intercenter support teams, hardware, and facilities.

The DRF was developed for detailed data requests by MSFC and JSC data users.

A Data Support Organization (DSO) was established to provide for overall management of data acquisitions, data processing, data dissemination, data display, and overall facility operation.

The data processing and handling capability was based upon the quantity of data necessary to perform anticipated support for scientific and engineering data. Mission Operations and Computation Laboratory Planning Meetings were held and tradeoffs were conducted for methods of handling the unprecedented quantity of data using existing center capabilities where possible.

Data priority procedures were established if overloading of the data systems should occur. In the event of technical problems (computer, etc), power failures or other anomalies, contingency plans for receipt and processing of high priority data were established.

Contingency priorities for engineering data were implemented early in the mission, which resulted in low output of scientific data processing. In this area, the job was underestimated resulting in delays in obtaining and processing scientific data. Cost was a limiting factor. A lesson learned from this would be separation of these data systems to prevent this conflict in the future. Further, end-to-end data flow demonstrations were not completed pre-mission. This illustrates that management attention must be given to ground data support problems and readiness schedules at the same level that flight software and hardware problems now receive.

c. Historical Support Facility Development Summary. As discussed in the Systems Operations Summary IV.A.1, the support facilities for Saturn at MSFC existed. Expansion of these facilities to support Skylab while retaining, or increasing, the Saturn support capability was necessary. Operations Support Planning Meetings were held to determine methods to be used to provide expanded support while using existing facilities and capability.

Facilities at HOSC included console systems, Support Action Centers, Management Rooms, Wind Room, Trajectory Analysis Room; communications and data lines to KSC and JSC existed to support activities discussed in the previous paragraphs. The Computation Laboratory at MSFC, located in the same building with the HOSC, was made available for expansion to accommodate the increased requirements, with the Slidell computer facilities available for overflow data processing.

Expanded physical plant capability at MSFC included additional computer capability and rearrangement of the floor plan at HOSC to accommodate additional MSG support personnel. The number of consoles was increased, conference work areas were established, additional communication capability (internal MSFC, and to JSC) was provided, and additional digital TV displays with switching matrix capability were provided within HOSC and selected remote locations on the MSFC complex.

B. Operations Support Objectives

The Mission Operations objectives of MSFC, as an integration center with hardware development responsibilities, were to:

- Provide engineering technical support to prelaunch, launch, and flight operations activities,
- Plan and develop a data management system to enhance technical support and to supply science data to users, and
- Provide adequate facilities (hardware and software) for mission support.

C. Operations Support Preparation

The activities discussed in this section are those used to prepare for mission support and fall within the following major categories:

- Analyze instrumentation and control for onboard systems monitoring and management during the mission,
- Develop mission support requirements and perform data management planning and implementation, and
- Provide necessary facilities (hardware/software) at MSFC to support these functions.

1. Systems Operations Analysis. Analyses were performed to ensure that monitor and control capability of onboard systems was compatible with mission operational modes, activation sequences, network coverage, mission planning and experiment scheduling.

a. Operational Instrumentation Analyses. These analyses were performed by identification of tasks required to be performed by ground or flight crews in the areas of systems and experiments activation, management for normal operations, contingency procedures, deactivation, and alternative means of accomplishment of mission objectives.

(1) Monitor and Control for Mission Support Tasks. Operations support tasks were identified, and required onboard measurements and controls were analyzed to ensure capability existed to perform identified tasks. Processing and display of the parameters was addressed in a general way to assist in sizing the facilities. Further analyses were performed on adequacy of specific onboard instrumentation and command capabilities to perform the support tasks defined. As a result, recommended changes in instrumentation and controls were made, and in some cases these changes were implemented. Membership of Mission Operations personnel on intercenter discipline panels were used to relay results of this activity to other centers and the MSFC discipline design organizations. For future programs to decrease costs, reduce design impacts, simplify operation and reduce schedule impacts, this effort should be started earlier in the program planning with vigorous schedule and milestone implementation by Management Program Reviews.

(2) Malfunction Detection and Workaround Analysis. The follow-on phase of analysis of instrumentation and controls for mission support was a top-down functional malfunction analysis. Emphases was placed on methods of detection and corrective actions available, with consideration given to redlines, constraints, and preliminary rules. The functional approach was chosen to provide operational visibility and a cross-tie with failure mode and effects analysis. This activity was provided to the SOCARs for the major disciplines by the Module Contractors and mission operations representatives. At the time of MSG formation, formal documentation of the analyses ceased and MSGs phased into the activity, generating the MSFC inputs to Mission Rules.

b. Operations Constraints and Mission Rules. This activity involved early identification of those constraints and limitations inherent in the design that would impact planning or methods of operation. Generally, these limitations and constraints were divided into those affecting prelaunch test and launch commit, or those affecting flight operations and planning.

(1) Mission Constraints and Systems Limitations. In conjunction with the instrumentation and control adequacy analysis, mission constraints, and systems limitations were identified. The constraints were separated into Prelaunch Operational Constraints and Mission Constraints, which were retained to provide inputs and assist in review of Mission Rules and Flight Plans. A concurrent activity, Commit-to-Launch criteria identification, was supported.

(2) Launch Mission Rule Inputs. MSFC launch mission rules were formally documented in the "Launch Mission Rule Input Document" which contained the rationale for the rules, redline data, and other background information. This activity evolved from the initial prelaunch constraints activity and was the official MSFC method for inputs to the KSC Launch Mission Rule Document. During countdown demonstration and actual countdown, mission rule coordinators were provided at HOSC to

monitor the launch operations communication loops at KSC for redline violations, or other problems, for Saturn launch vehicle and Skylab.

(3) Flight Mission Rule Inputs. The flight mission rule input and review preparation by MSFC was begun using the Malfunction Analyses Mission Operations Design Support approach as a basis for ensuring that flight rules were prepared for malfunction impacting subsystems, subsystem and vehicle interfaces, and major mission objectives. Mission Operations personnel were active on intercenter discipline panels, in design reviews and crew station reviews.

A planned flight Mission Rule Input Document was abandoned in favor of a Flight Mission Rule Change Package, which was developed by discipline areas using the MSG concept, and the more important of the rule items were covered in manned management criteria during the mission.

c. Operational Performance Data Assessment and Validation. Operational parametric data was gathered and provided to the Operations Data Group (ODG), consisting of all hardware development centers, for incorporation into the Operations Data Book (ODB). A statusing function of CCB actions was used to ensure that the lag between the ODB data and actual configuration was minimized, and final configuration and test data was available and documented.

2. Data Management. The data management function accomplished by the DSO, required interfacing with other centers and coordination of activities related to development, documentation, and implementation of all data requirements. Statusing, coordination, acquisition, and dissemination of data to users were general responsibilities addressed in development of the data management system.

a. Data Management Planning. Initially, a plan was developed to establish the approach to be taken in data management. The Skylab presented an unprecedented quantity of data with a multiplicity of data users and data types. Roles of the various NASA Centers and their supporting contractors were addressed in general terms to determine data flow, priorities, and processing facility requirements. Mission Operations and Computation Laboratory meetings were held to develop plans and criteria to increase the data handling capability, and obtain maximum use of the existing facilities.

b. Program Support Requirements. Program requirements levied at NASA Headquarters upon all NASA Centers and support agencies were documented in the PSRD. The initial inputs to the PSRD were baseline intercenter support requirements involving long lead time or program impacts. These requirements were refined as more definite program information was developed.

c. Data Requirements. A DRF was developed as a standardized method of requesting data for all MSFC/JSC data users. The DRF system

was jointly agreed upon by MSFC and JSC for levying data requirements between the two centers; however, program/mission level support requirements (i.e., communications, data lines, TV, etc.) were documented in the PSRD.

The DRF requirements were put into a computerized data base, called the Automated Data Requirements System (ADRS), which was developed for statusing and control of all MSFC DRFs.

The ADRS is a computer programmed system that used the Univac 1108 computer. The programming, as established, provided remote access to the 1108 computer through a remote DCT 500 terminal located in the HOSC Data Management Room for mission support. The ADRS allowed the Data Requirements Group the flexibility to query the data base for data requirements for processing, requirements flow, requestor status, and data completeness.

The DRF specifications for processing ADDT data were put on the ADRS tapes; then the ADDT data were processed using the ADRS tapes to output the DRF requirements.

d. Data Support Organization. The DSO was developed to provide overall MSFC management for all Skylab data related functions. The DSO was subdivided into the following groups:

- Data Processing Group
- Data Requirements Group
- Data Acquisition and Scheduling Group
- Data Dissemination Group
- Facilities Group
- MOPS Group

(1) The Data Processing Group was composed of

- Processing Manager,
- Production,
- Scheduling,
- Operations, and
- Real-Time Support Coordinators.

The processing manager position was staffed around the clock by a representative from the computation laboratory. The group responsibilities include planning, implementation, operation and assessment of Skylab data operations functions.

(2) The Data Requirements Group consists of the Data Requirements Manager (DRM), the Data Requirements Coordinator (DRC) and the Data Requirements Processor (DRP). The group's responsibilities included receipt, assessment, coordination, and processing of all data requests. In addition, the DRM had overall responsibility for the Data Management Room (DMR) operations for requirements tracking and statusing, data acquisition tracking and flow, and the dissemination of all Skylab

data. The requirements group positions were manned 24 hours per day during pre-mission simulations and for the duration of Skylab missions.

(3) Data Acquisition and Scheduling Group consisted of tracking of data from the remote sites through GSFC to JSC and the eventual scheduling of shipment of this data to the MSFC either by electronic data transmission or shipped in a hard form. Data Acquisition consisted of manning two data acquisition positions 24 hours per day for seven days a week.

(4) The Data Dissemination Group consisted of a dissemination clerk and his assistants. This under the direction of the DRM was responsible for receiving, sorting, and delivering MSFC responsible data during all mission phases on a 24 hour per day basis.

(5) The Facilities group consisted of the Facility Manager (FM) and a Display Specialist (DS). This group was responsible for the implementation, control, and maintenance coordination of the HOSC real-time data, display, communications, and facility systems. The FM was specifically responsible for ascertaining and evaluating the problems associated with the various systems, and for coordinating solutions to the problems. The DS was specifically responsible for assisting in implementation of the display system requirements to satisfy needs of the Console Engineers (CEs) for the Operations Support Room (OSR) and for supporting the CEs, with regard to technical problems, throughout the mission. The FM position was manned around the clock with two FMs required at launches. The DS position was manned on the first shift seven days a week with around-the-clock coverage from launch through rendezvous.

(6) The MOPS Group consisted of a Controller and four operators. This group was responsible for acquiring planning and telemetry data in a near real-time environment. Data requests were primarily of a one time nature, with secondary emphasis on recurring requests. Contingency operation was implemented in the event of the loss of real-time data display capability. The MOPS controller was responsible for receiving requests and subsequent assignment to terminal operator, and notification of the requestor upon completion of their data request. Logs were kept, noting the operational status of the computer applications and terminal hardware, as well as the data requests.

The MOPS controller and operator positions were manned around the clock during manned Skylab phases and on an "as required" basis during unmanned phases.

e. Onboard Systems/STDN Compatibility Analysis. Analyses were performed to assess operational means of retrieving scientific data using the defined onboard system design by determining required ground tasks to be performed. Onboard measurement sample rates, and the frequency and duration of the STDN site contacts were compared to

the identified ground tasks to surface any network constraints for planning purposes. The onboard tape recorder capabilities were of particular concern for those orbits having long durations with no STDN contacts. A computerized RF analysis and procedural tool (COCOA) was adapted to operations usage to determine which antenna should be chosen for various vehicle altitudes, maneuvers and tape dump management.

Other results of these analyses were recommendations for use of Apollo Range Instrumentation Aircraft (ARIA) and reactivation of the Newfoundland site to provide compatible ground station coverage for the missions.

f. Data and Communications Systems. Provisions were made for the following types of communications and data to be provided:

(1) Communications Systems. Voice communications loops were available between JSC and MSFC to provide mission status, resolution of technical problems, and coordination of data transmissions.

Mission activity was monitored via the Flight Director (FDIR) and air-to-ground crew voice, Ground Operational Support System (GOSS) loops. These loops were extended to several remote MSFC locations and contractor facilities.

The resolution of technical problems, as well as conferencing capability, was provided by seven JSC-MSFC long lines, HOSC Conference (HOSC-C), ATM Experiments (ATM EX), Flight Operations Management Representative, Propulsion (PROP), and Networks (NTWK), which provided the HOSC direct communications with the FOMR at JSC. In conjunction with speaker phone equipment, these long lines provided the capability for MSFC MSG leaders and MCC Flight Controller personnel to resolve many problems requiring quick reaction solutions.

Coordination of data transmission was accomplished over five JSC-MSFC long lines: Skylab Terminal System Conference (STS CONF), Mission Control Center Configuration Supervisor Conference (MCS CONF), Mission Data Retrieval System Conference (MDRS CONF), Data Coordination (DATA COORD), and Data Manager (DATA MGMT).

The DATA COORD and DATA MGMT lines were primarily used for real-time scheduling and problem solving, while the other three were primarily used to coordinate stored data requirements (including MOPS). Several voice loops were provided within the HOSC for internal conferencing capability. Internal (INT) was extended to all call director instruments to provide a "general call" capability within the HOSC. The Display Loop (DISP) was used primarily by Computation Laboratory personnel for coordination of real-time data display. The Operations Director (OD) loop provided an open line between the OD and key operations support personnel. In addition, three general conference loops were provided for extended conversations between HOSC personnel, CONF A, CONF B, and CONF C.

Station to station communication within the HOSC and to selected remote MSFC sites was provided by the Private Automatic Branch Exchange (PABX) system. This system, installed specifically for Skylab Mission Support, consists of three digit extensions available at every work station within the HOSC, and provided access to MSFC Centrex System, local Federal Telecommunication System (FTS), and Huntsville exchanges. During the launch/insertion phases of the Skylab Mission, long-line communications were provided from KSC to MSFC; Operational Intercom System (OIS-1 through OIS-8) were used for monitoring of the countdown/launch phase; Data Core Coordination Line (DCCL) for real-time data coordination; and Marshall Skylab Representative (MSLR), and Saturn Launch Vehicle Representative (SLVR) provided direct communications for problem resolutions and conferences.

In addition, the Launch Information Exchange Facility (LIEF) telephone system, available to most work stations within the HOSC, provided long distance communications. The LIEF system was retained from the Apollo/Saturn Program and served MSFC in general as well as in support of the Skylab mission.

(2) Real-Time Data System. HOSC received real-time data from Skylab during the entire mission. The Mission Operations Computer (MOC) at JSC received and reformatted the data from the remote sites, buffered and transmitted it to the HOSC at an average rate of one sample/sec. This rate varied as a result of data line loading by very active parameters. In order to reduce line loading, the RSDP incorporated a software algorithm that tested each parameter before transmission to the MOC, compared the data change to a preset value (PCM count change), and transmitted or discarded redundant data in real time. This preset value established a corridor which the counts had to exceed before the measurement value would be transmitted. This corridor could be updated (widened or narrowed) by a decision of the Flight Controller. The data to MSFC depended on the corridors chosen. JSC had the capability to see every sample of the measurements transmitted; however, the HOSC could only see the data approximately once per second.

The real-time data was used by the MSFC computers to drive various displays. One computer (Consoles Program) was used to drive the event lights, analog meters, strip charts and decimal indicators while a second computer, Digital to Television Program (D/TV), was used to drive the digital television equipment. If the main Central Processing Unit (CPU) for the D/TV malfunctioned, a third computer was brought on-line as a backup; however, it reduced the D/TV capability from 20 to 8 channels because of the reduced memory availability. Display format, as well as other display requirements were developed and documented in the HOSC Display Plan and the Data Users Handbook. When the CSM was activated, the MOC was not able to deliver display data to the MOCR and simultaneously transmit all the data MSFC required. During these times a MOPS contingency plan was implemented to supply data to the MSGs. In addition, the TV microwave channel was used to provide MOCR displays in the HOSC. These displays were controlled by the OSM. The D/TV and

other pertinent data was disseminated to the MSGs via the video matrix. The matrix had 80 outputs which could select 1 of 59 inputs. The outputs were TV monitors located in the consoles of the OSR, in each Conference Work Area (CWA), the Problem Resolving Room (WAR) and other remote areas of supporting activity. Most areas that had an output monitor had a matrix selector switch that allowed selection of its inputs. The Master Matrix Panel in the Information Control Room (ICR) allowed complete control over all inputs and all outputs. An auxiliary control panel located in the OMR allowed switching of the matrix inputs to the remote areas and the OMR.

Other video data included items such as site acquisition and loss times, Mission Status Generator, downlink TV from the spacecraft, Network Video; American Broadcasting Company (ABC), Columbia Broadcasting Company (CBS), National Broadcasting Company (NBC), and Public Affairs Office (PAO) news and press conferences from other NASA Centers.

(3) All Digital Data Tape System. The ADDT system was used to transmit downlinked data from the remote site to JSC and from JSC to MSFC. The ADDT data were received at MSFC either by electronic transmission or by air transportation.

At MSFC, the ADDT data were processed to output:

- Engineering Data Books,
- User Tapes (9 and 7 track)-Fixed and Compressed,
- Inputs to Special Analysis Programs
(Engineering and Scientific),
- Autoscan Outputs.

The initial plan for electronic transmission was to transmit four six-hour blocks for each day from the JSC data base. This was done from computer to computer.

The JSC ADDT computers were loaded down, especially when the site input and MSFC output were occurring simultaneously. Therefore, two batches were transmitted by electronic transmission, and the remaining two batches were sent by air transportation. In the second manned mission, the computer to computer electronic transmission was terminated; all the batches were sent by air transportation.

In the first part of the third manned mission, ADDT was received by tape to tape electronic transmission. Thus, the tapes were transmitted independent of the JSC ADDT system without loading it down. This system proved adequate to bring in data for on-going mission requirements.

(4) Mission Operations Planning System. Four MOPS terminals were provided at the HOSC for data retrieval from the JSC computers. Each of the terminals was manned on a 24-hour daily basis during the manned mission periods, and reduced manning schedules were

employed during unmanned periods. The primary MOPS use involved accessing the MCC MDRS for the fulfillment of specific data requests (by time interval) selected from a fixed format library of discipline-oriented tabular and graphic displays. The MDRS data bases were loaded in alternate sequence, so when the current data base reached 90 to 95 percent of its capability, the static data base was purged to become the new current data base. The former current data was then closed to inputs. This assured a file of chronologically-sequenced data for the latest 18 to 36 hours of telemetry from Skylab. As MSG personnel became more familiar with the data requirements for their particular fields of interest, special format reconfigurations were used to output only those parameters of interest, rather than relying on fixed formats.

The Activity Scheduling Program (ASP) was used primarily to secure daily flight plans for review of planned activities; as-flown flight plans for evaluation of completed activities; sunrise/sunset tables and predicted site acquisition tables to be used in experiment planning and real-time support scheduling; and trajectory print displays to establish revolution start times, equator crossings, beta angles, flight path angles and geodetic coordinates to be used in maintaining status board entries, experiment scheduling, and various other functions associated with review of mission requirements. Periodic requests for such outputs as camera/film use and general pointing information were generated to fill specific needs of MSG members.

Additional access was provided to the Data Acquisition Statusing System (DASS), Crew Procedures Data System (CPDS), and the MDRS Trajectory application on a limited basis. The Online Math Processor (OMP) was also available.

Near real-time data output from MOPS served to bridge the time interval between the HOSC real time displays and the availability of data locally via ADDT. In addition, contingency procedures were developed to provide non-real time data in lieu of real-time displays occasioned by loss of display capability. The contingency mode was entered upon the loss of real-time displays for two consecutive station passes, and continued until such time as displays were restored. Contingency data distribution was accomplished via the Administrative Support Center (ASC).

(5) Voice Transcripts. Quicklook Voice Transcripts (Q/L) consisted of real-time and dump crew voice and were electronically transmitted in near real time to MSFC via long-line from JSC. The voice data were not technically edited or accurately time annotated and was output in a time frame that enabled their use for quick trend analysis. The transcripts were received at MSFC on the Magnetic Tape Selectric Typewriter (MT/ST), which was located in the data room of the HOSC. Two shifts of MT/ST operators were required to man the MT/ST system during the manned phase of each mission. When approximately two hours of voice data had been received, the MT/ST operator assigned a batch number to the data. The batch was then taken to the ASC, which reproduced the

quick turnaround copies for advance distribution to the Mission Requirements Review Room (MRR) and the OSM. At the end of second shift when all transcripts for the day had been received, the MT/ST operator assembled the real time and dump transcripts into one package. The data were then submitted to the repository for final reproduction. Reproduction of the transcripts was done on the midnight shift and returned to the data room where it was placed in proper data bins, and the transcript copies were available for recipients by 0800 AM each day. The original transcripts were submitted to the DRM who placed them in the Master Q/L Transcript File maintained in the DMR.

Edited Voice Transcripts were technically edited and accurately time-annotated transcripts compiled from the Q/L voice data at JSC. The transcripts ran approximately two weeks behind real time and were primarily design for postmission analysis where more accuracy is required. The method of delivery for these voice data to MSFC was via air mail from JSC. On receipt of the transcripts at the HOSC Data Room, the Data Dissemination Clerk (DDC) sent the data to the repository for reproduction and then returned them to the data room where they were placed in the proper data bins for pickup by requestors.

(6) Facsimile. Transmittal of written material between MSFC and FOMR at JSC was necessary due to the technical content and procedural nature of the data interchange. Therefore, the planned Mag-nafax and a high speed Long Distance Exchange (LDX) machine were used for action requests, responses, flight plan changes, comments to flight plan, procedural changes, etc., by MSGs and the ODs. Facsimile transmission was also provided between MSFC and prime contractors.

(7) Photographic Data. A requirement was established with JSC to receive reproducible masters of all flight film returned by the astronauts at the end of each manned mission. The master was received at MSFC and submitted to the Photographic Laboratory for processing to satisfy MSFC photographic requirements. The photographic plan developed for the Skylab Program defined the flow, tracking, and coordination of all Skylab flight film. Photographic requirements levied on MSFC by the various technical disciplines were greater than anticipated for SL-1/2 due to extensive photography taken during flyarounds and EVAs, which were used for analysis of anomalies experienced during the launch of SL-1. The MSFC photographic requirements for SL-4 were also greater than expected due to an extension of the SL-4 mission.

(8) Video Data. A requirement was levied on JSC (before SL-1) for a copy of all flight video from the Skylab Program. The video copies were merged (real time and dump) on two-inch video tapes and shipped (via commercial air) to MSFC every two or three days. These were known as Master Merged Video Tapes, and were used by the communications facility to produce 16mm kinescopes and video cassettes. The 16mm kinescope copy was sent to the MSFC Photographic Laboratory where copies were made at Mission Operations request to satisfy video

requirements. Copies of the video cassettes were provided to satisfy video requests when specifically requested.

3. Operations Support Facilities, Training, and Manning

a. Operations Support Planning and Procedures. The method used for providing hardware and software facilities was to adapt the HOSC and Computation Laboratory for use with Skylab and to interface with contractor facilities for mission support on an as-requested basis, and at the same time retain Saturn vehicle support capability. Interface with the LIEF and Slidell Computer Facility was also available to provide mission support. A manning plan was generated and used in sizing the facility. A HOSC Facilities Plan was generated and facilities were provided on a 24-hour basis in which MSG personnel, operations staff, console engineers, administrative personnel, data support, data dissemination, and module representatives were located. The development of the functions and their interfaces were defined in the "Operations Coordination Procedures" that defined the positions and duties of support personnel, and their documentation, communication procedures, etc. These were streamlined through their use in simulations and subsequent mission activities. The HOSC floor plans showing locations of the various functional activities are shown in Figures IV.C-1 and IV.C-2.

b. Training and Simulations. A training plan was developed to prepare for mission support. The JSC simulation support and KSC test support schedules were used in scheduling HOSC activities. Due to time limitations and hardware problems only one "paper" simulation involving only MSFC was scheduled in preparation for simulations and mission support.

(1) Classroom Training. Video-taped familiarization lectures for onboard systems were required in varying degrees for the MSFC personnel involved in mission support. Additionally, lectures on the use of HOSC facilities and communications were presented. Specialized training for HOSC Console Engineers and MOPS terminal operators was conducted. Training was also provided for MSFC mission support personnel engaged in FOMR and Mission Evaluation Room (MER) activities at JSC.

(2) On-the-Job Training. Activities requiring on-the-job training included FOMR, MER, and HOSC Communications, Console Engineers, and MOPS operators. Some on-the-job training was combined with early simulation exercises.

(3) Simulations. Simulations for the Skylab program involved numerous growth levels. Initially, the exercises involved only the Operations Staff, and provided familiarization with Operations Coordination Procedures and Communications. A paper simulation that involved two MSGs at once, was the next step. The simulation provided a simulation staff for problem generation, data support, and simulation of FOMR and JSC voice inputs. The paper simulation exercised interfaces

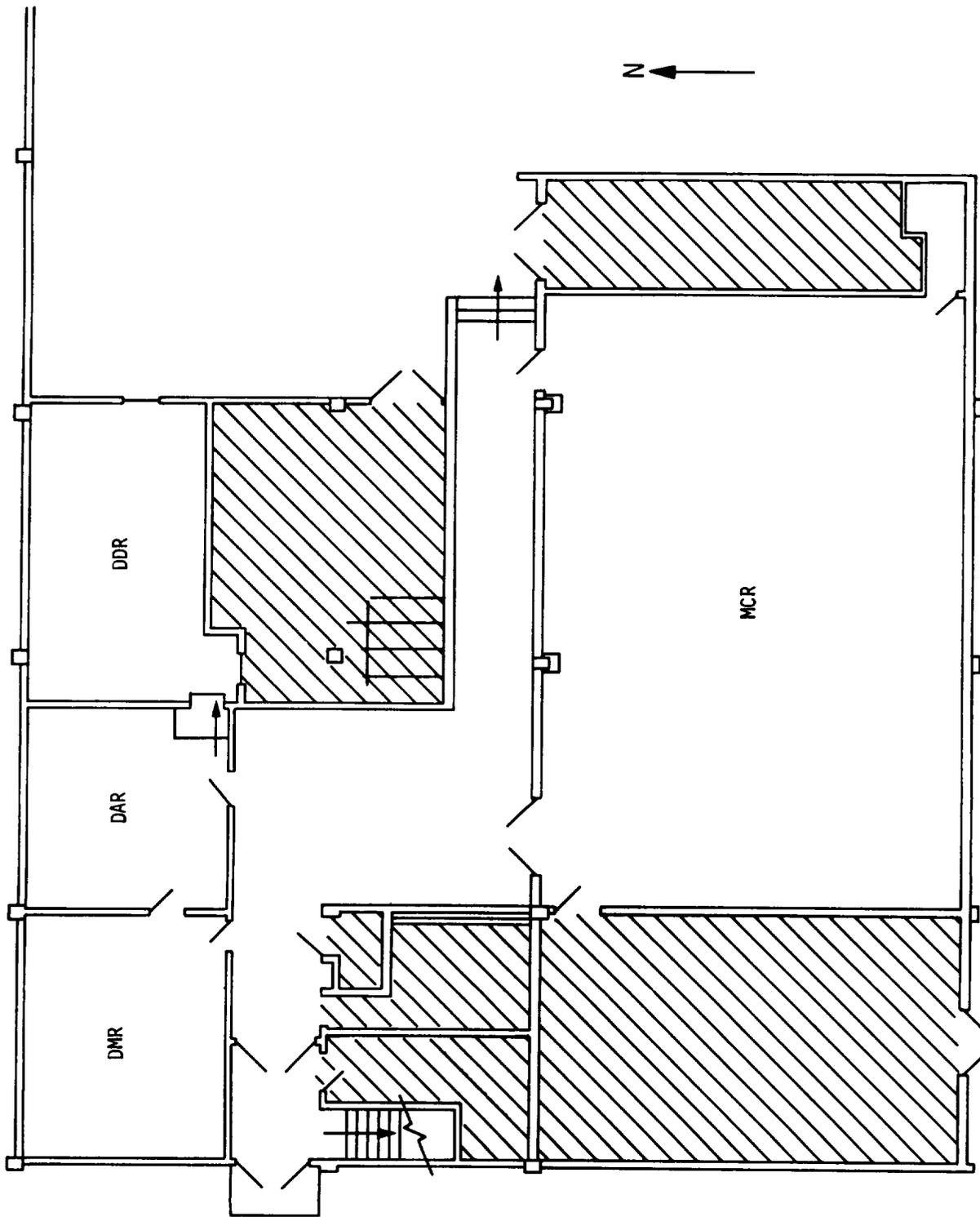


Figure IV.C-1 HOSC First Floor

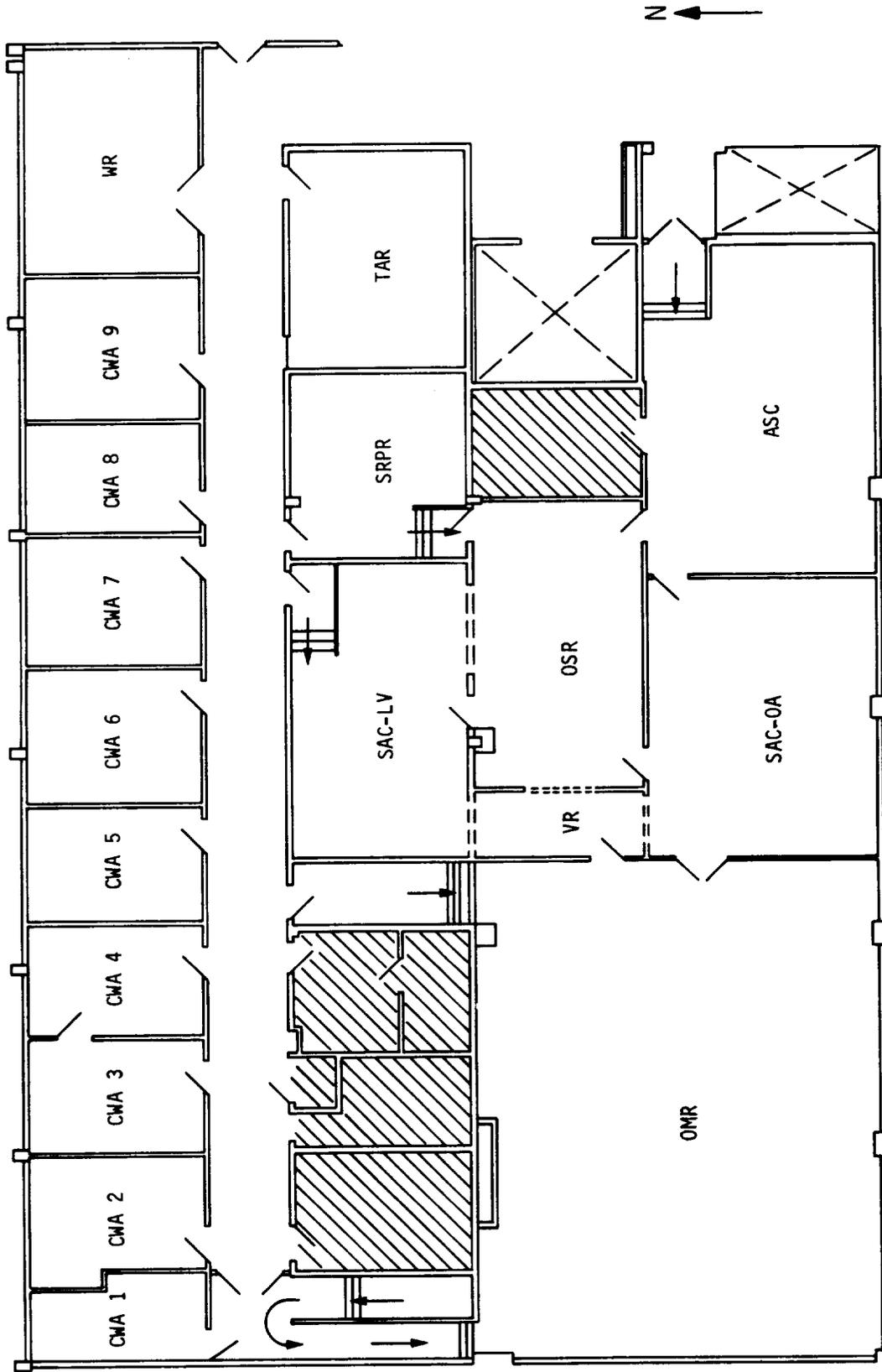


Figure IV.C-2 HOSC Second Floor

in MSFC, but did not involve any other center. Further simulation preparation in JSC paper simulations of various segments of the Skylab mission (e.g., liftoff and ascent, SWS activation, first day activities, etc). The next step was to support "full-up" simulations with data flow from JSC. A full data flow test and simulation was not available pre-mission due to problems in the data management software.

c. Mission Support. Software, hardware, and personnel requirements were tailored to support combined Saturn and Skylab activities. Launch support for SL-1, -2, -3, and -4 launch vehicles was concurrent with the SWS support and required additional facilities for support teams. The MSFC personnel at JSC manned the BSE position in the MOCR at MCC as they had done for Apollo launch vehicle support. Additional responsibility was given to these personnel for activation of SWS systems. Support Action Centers (SAC) were provided at HOSC for OA and Launch Vehicle team activities. De-orbit areas for the S-II and S-IVB stages, Engine, Stage, Wind, and Trajectory Analysis were functional rooms manned for launch vehicle support. The rooms at the HOSC were converted to support the OA experiments after launch phases. Launch vehicle prime contractors' facilities were tied to the communications and data links for technical and analytical support.

(1) Administrative and Engineering Support. Numerous administrative and engineering functions were required for mission support. Included were an Administrative Support Staff, an Operations Staff, Facilities Management, and a Data Management Staff.

(a) Administrative Support Staff. The group was responsible for operation of the ASC with the HOSC. Skylab Operations Library maintenance, receipt and logging of Facsimile data, typing, reproduction, and distribution of action requests and responses, were the major responsibilities that were required on a 24-hour seven day week basis during manned and unmanned phases.

4. Management Staff. The management staff at HOSC consisted of a Senior Operations Director, an Operations Director, an Operations Support Manager and an Assistant Operations Support Manager. Their function was to provide a management focal point at MSFC for mission support activities, assign problems to MSGs, and establish/arbitrate priorities.

The FOMR Staff positions filled by MSFC personnel were the Senior Program Representative, the ATM Experiment Engineer, the Corollary Experiment Engineer, and appropriate systems engineers.

5. Support Coordination Staff. The group consisted of a Support Coordinator, a Support Coordinator Assistant, a Personnel Locator, a Report Coordinator, a Mission Status Engineer, and a Staff Systems Engineer. Generally, their function was to locate key personnel; status, track, and coordinate responses; provide mission status, prepare daily and weekly reports; maintain communications with MSFC Center Management

and FOMR, and assure smooth operation by insuring responses were properly logged and submitted when due.

6. Data and Facilities Management Staff. The group included a Facilities Manager, Data Support Manager, a DRM, a Data Processing Manager, a Data Acquisition Specialist, and a Data Dissemination Clerk. Their functions included acquiring data, establishing data priorities, manning MOPS, processing data, and statusing, tracking and disseminating processed data. Data types included microfilm, user tapes, strip charts, data book printouts, film data, and voice transcripts. The Facilities Manager position was staffed 24-hours a day to insure the physical plant functions were maintained in operational configuration. Interfaces with other center and base operations were maintained.

7. Mission Action Requests and Problem Reporting. The methods used in assigning problems at the HOSC involved Mission Action Requests (MARs) generated at the FOMR and Action Requests (ARs) generated at HOSC. These forms and their disposal are discussed in detail in the Operations Coordination Procedures. All action requests were included in a weekly report and required formal anomaly closeout.

The number of MARs handled by MSFC was 1994 for the total Skylab mission. Table IV.C-1 categorizes the types of actions and is tabulated by areas of assignment. The number of ARs generated by MSFC was 2347 for the total Skylab mission. These are tabulated by category and area of assignment in Table IV.C-2. The combined total of action traffic is similarly illustrated in Table IV.C-3.

To illustrate the rate of accumulation of MARs and ARs as the mission progressed, Figures IV.C-3 and IV.C-4, respectively, plot the number of requests against mission time.

Table IV.C-1. MAR Composite Summary, Total Skylab Mission

MARs	ACTIONS (MARs)	ANALYSIS OR DATA INPUT REQUESTED	FLIGHT PLAN RELATED	PROCEDURE RELATED	DOCUMENTATION RELATED	STOWAGE RELATED	HARDWARE PROBLEM RELATED
ECS/TCS	326	193	48	47	32	6	90
APCS	289	164	42	41	36	6	56
EPS	249	126	42	40	35	6	58
STRUCTURAL & MECH	180	101	29	26	18	6	68
I&C	164	83	29	22	24	6	34
CREW SYSTEMS	168	78	30	27	24	9	37
CONTAMINATION	98	40	25	5	17	6	9
ATM EXPERIMENTS	200	96	46	25	25	8	61
ATM TCS	96	38	32	2	18	6	11
COROLLARY EXPERIMENTS	204	94	41	24	32	13	30
ASTN	5	5	0	0	0	0	2
AERO	3	3	0	0	0	0	0
MDAC-W	7*	4	1	1	0	0	1
MDAC-E	2	1	0	1	0	0	0
IBM	5	4	0	1	0	0	1
MMC	1	1	0	0	0	0	0
LAUNCH VEHICLES	2	1	1	0	0	0	0
TOTALS**	1194	1032	366	262	261	80	458

*Provide Hardware - 1

**Contained in the totals are 63 actions common to all MSGs.

Table IV.C-2. AR Composite Summary, Total Skylab Mission

ARS	ACTIONS (ARS)	ANALYSIS OR DATA INPUT REQUESTED	FLIGHT PLAN RELATED	PROCEDURE RELATED	DOCUMENTATION RELATED	STOWAGE RELATED	HARDWARE PROBLEM RELATED
ECS/TCS	244	104	54	22	52	12	44
APCS	294	145	60	23	54	12	72
EPS	268	116	61	24	55	12	66
STRUCTURAL & MECH	220	90	49	15	53	13	52
I&C	212	82	50	11	57	12	42
CREW SYSTEMS	217	78	51	17	55	16	38
CONTAMINATION	172	51	49	6	54	12	21
ATM EXPERIMENTS	226	79	56	18	59	14	50
ATM TCS	174	57	49	4	52	12	21
COROLLARY EXPERIMENTS	279	76	58	13	114	18	30
ASTN	6	4	1	0	1	0	4
ASTR	3	2	0	1	0	0	2
AERO	2	2	0	0	0	0	1
MDAC-W	14*	11	1	0	0	0	6
MDAC-E	8	7	1	0	0	0	4
MMC	8	6	2	0	0	0	3
TOTALS**	2347	910	542	154	606	133	456

*Provide Hardware - 2

**Contained in the totals are 159 actions common to all MSGs.

Table IV.C-3. Total MSFC Actions, Skylab Mission

	ACTIONS	ANALYSIS OR DATA INPUT REQUESTED	FLIGHT PLAN RELATED	PROCEDURE RELATED	DOCUMENTATION RELATED	STOWAGE RELATED	HARDWARE PROBLEM RELAGED
ECS/TCS	570	297	102	69	84	18	134
APCS	583	309	102	64	90	18	128
EPS	517	242	103	64	90	18	124
STRUCTURAL & MECH	400	191	78	41	71	19	120
I&C	376	165	79	33	81	18	76
CREW SYSTEMS	385	156	81	44	79	25	75
CONTAMINATION	265	91	74	11	71	18	30
ATM EXPERIMENTS	426	175	102	43	84	22	111
ATM TCS	270	95	81	6	70	18	22
COROLLARY EXPERIMENTS	483	170	99	37	146	31	60
ASTN	11	9	1	0	1	0	6
ASTR	3	2	0	1	0	0	2
AERO	5	5	0	0	0	0	1
MDAC-W	21*	15	2	1	0	0	7
MDAC-E	10	8	1	1	0	0	4
IBM	5	4	0	1	0	0	1
MMC	9	7	2	0	0	0	3
LAUNCH VEHICLES	2	1	1	0	0	0	0
TOTALS*	4341	1942	908	416	867	205	914

*Provide Hardware - 3

**Contained in the totals are 222 actions common to all MSGs.

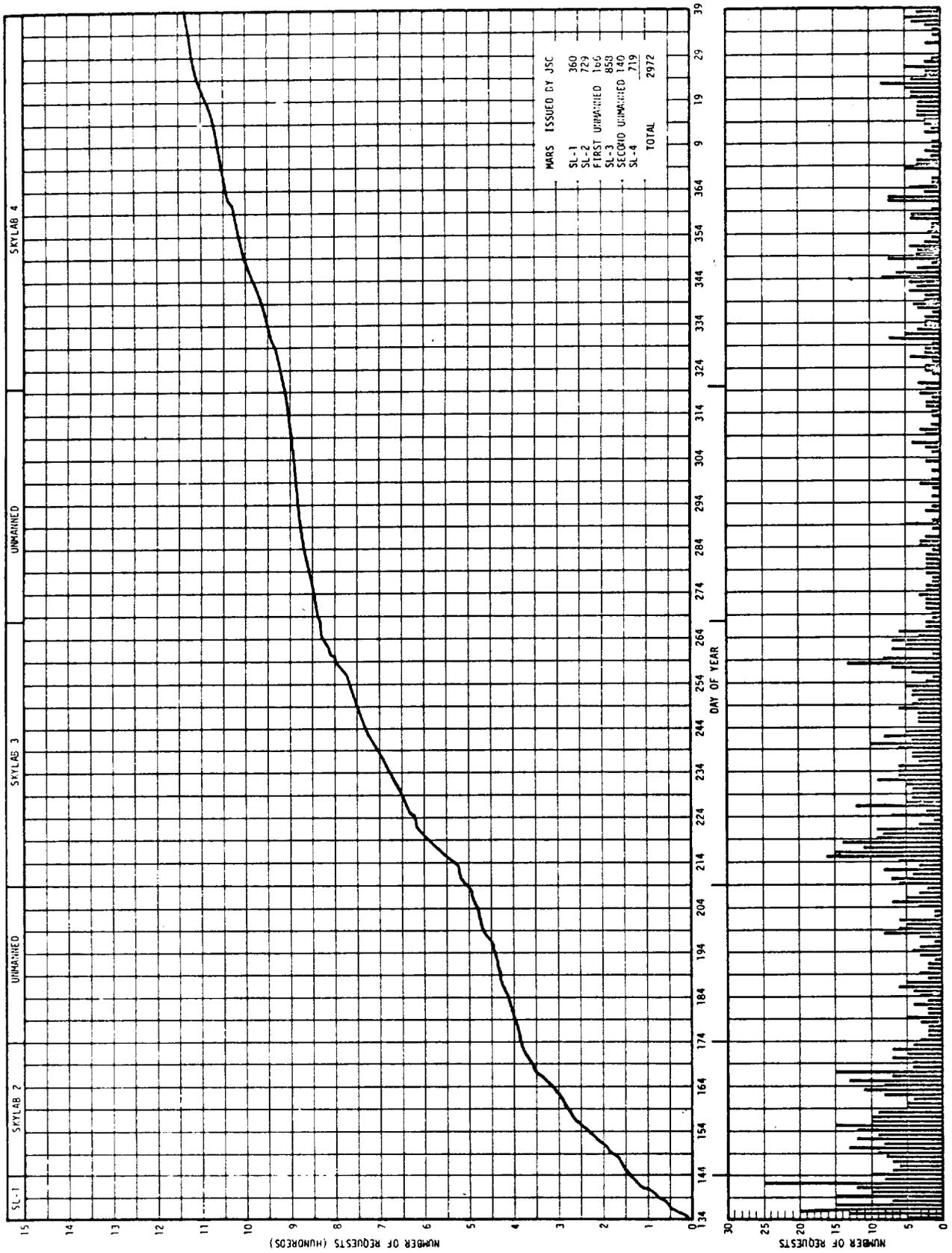
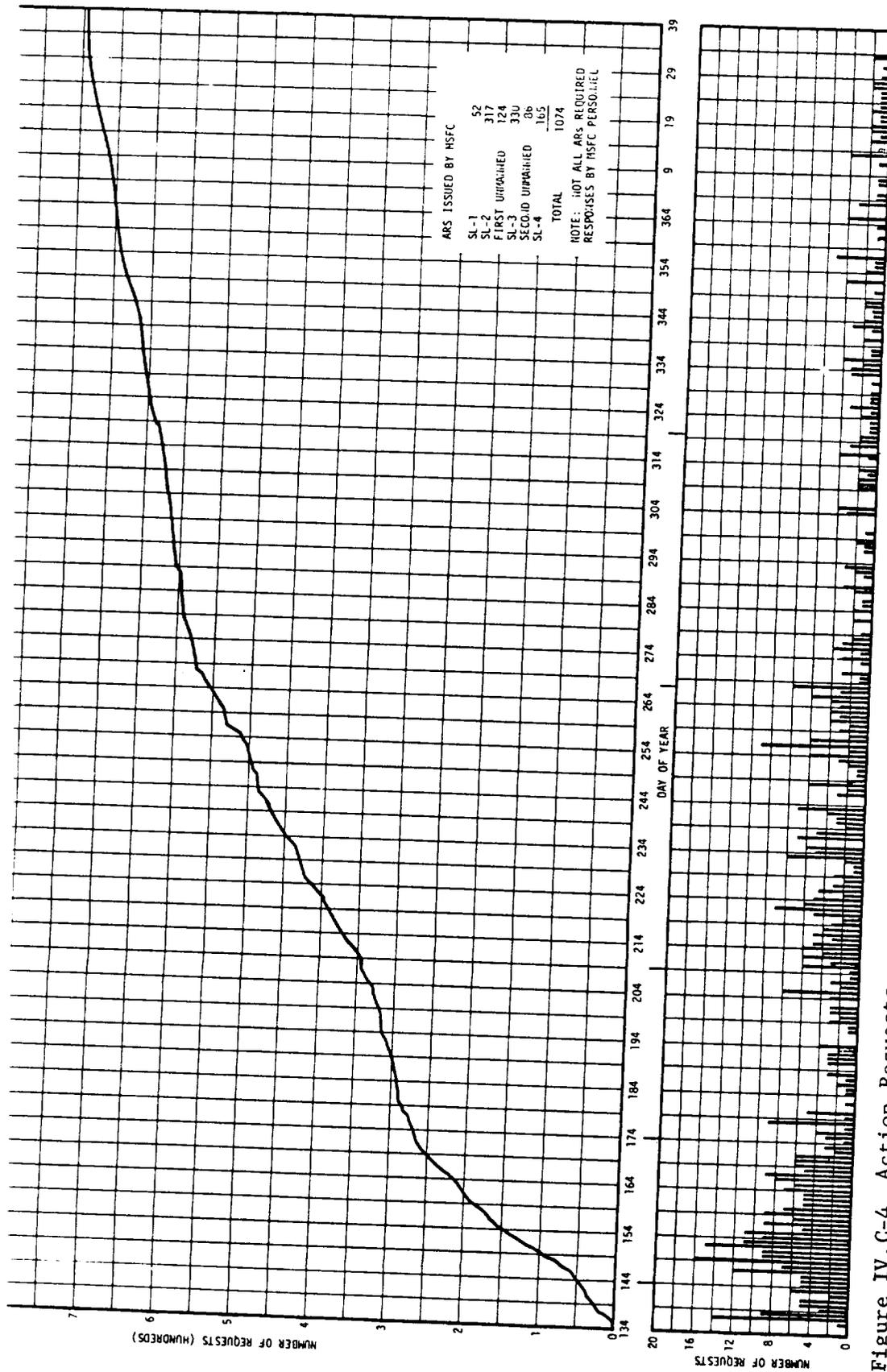


Figure IV.C-3 Mission Action Requests



D. Conclusions and Recommendations

1. Conclusions. Pre-mission planning was changed significantly in three specific areas after the mission began. The areas were as follows:

a. Operations Management. Two staff positions were established after the mission began. One was the Senior Operations Director who was in charge of MSFC support activities at the FOMR and at the HOSC. The second position was that of the Operations Director who was the Senior Official per shift and was responsible for HOSC support by pursuing on-going problems and establishing priorities.

b. Work Schedules. Original plans were to staff the HOSC 24-hours per day and require a MSG work force 40 hours per week, or as required for problems. As a result of the many problems, a seven day week, 24-hour day schedule was initiated for most MSGs. This required the addition of almost three times as many persons as were originally planned in some areas.

c. Data Flow. The ADDT transmission was not satisfactory until late in the mission. End-to-end data flow testing was not completed satisfactorily before the mission.

2. Recommendations.

a. Staffing should allow for contingency. It is easier to cut down on staffing than it is to build a staff after problems occur.

b. Initiate early planning for end-to-end data flow testing by exercising all involved elements and allowing adequate time for software changes and validation that inevitably result from early testing.

c. Operations (Facilities, Software, Plans, etc.) should be subjected to the same rigid design review system to which flight hardware is exposed.

V. Program Assurance

V. PROGRAM ASSURANCE

A. Planning and Scheduling

1. Background Summary. The official release of the first launch schedule (ML-4) by NASA Headquarters on March 23, 1966, marked conclusion of the preliminary planning development phase of the AAP (Skylab) program, and introduced the need for a project oriented management structure within the individual center authority to implement the programs necessary for a firm mission commitment. A new type of program control organization was necessary to identify and assess the current status of program elements and focus management attention on potential program impact to the ML-4 schedule.

2. MSFC Management Participation. The MSFC Skylab Program Manager established an organization consisting of project managers from major module elements of the program: Orbital Workshop, Multiple Docking Adapter, Airlock Module, Payload Shroud, Apollo Telescope Mount, and Experiments. Additional organizations were established for the major discipline activities of Test Reliability, Quality Assurance and Safety; Engineering Integration; and Program Control. This MSFC Program Management Team was delegated specific responsibilities for every end item and support function required for successful accomplishment of the development and integration assigned to MSFC by NASA Headquarters. Each Project Manager, in addition to controlling and monitoring his assigned project/discipline duties, was assigned responsibility for developing and maintaining project schedule requirements in the subsystem level of detail necessary for successful program management. Included in these schedules were project level intermediate milestones, subsystem status, mockups, trainers, test articles, ground support equipment, flight articles, significant problems, special studies, technical and management interfaces affecting the project. These schedules were furnished to a central planning organization for compatibility, summary analysis and subsequent incorporation into the Skylab Management Center and the intercenter schedule publication known as "SARP" (Schedules and Resources Summary).

a. Skylab Management Center. The need for a Skylab Management Center or Control Room was established early in the program by the MSFC Skylab Program Manager. The Program Control Office was assigned the responsibility for developing an information display system to be used within the center. This information system was to have the capability of presenting detailed elements of the program in the level or levels necessary for effective program assessment, rapidly and in systematic order. Initial efforts produced a number of hardware-oriented displays adequate for identification of major program elements, but as new disciplines developed and integrated program requirements were defined (experiment payloads, configuration management, quality assurance, and Level 1 reporting), new and increased demands were placed on the reporting system. New techniques such as SARP, tabular matrix,

and modified PERT were employed to effectively deal with the increased display requirements.

b. Schedules and Resources Summary. A comprehensive and efficient management planning and reporting technique was implemented in January 1969, and proved effective throughout the tenure of the program. This Schedules and Resources Summary Plan, initiated by a NASA Headquarters memo, identified specific program elements, control milestones, and requirements established by Headquarters management and extended through each assigned center's responsibility. A monthly cycle was established for the preparation and submittal of each center Program Manager's input to the NASA Headquarters. Figure V.A-1 contains a specific listing of the MSFC responsible items.

General SARP Requirements. Each Center Skylab SARP book was organized into subject category sections containing all levels pertaining to that subject as follows:

- Center Summary Section. All three Centers.
- Project Sections. Each project section for MSFC and JSC contained all project, module, system schedules, and resource charts for Levels 2, 3, and 4.
- Experiment Section. For MSFC and JSC included all experiment development schedules for resource charts.
- Mission Summary Sections. For KSC, each mission included all charts pertaining to that mission for all levels.

Center Summary Level SARP Requirements.

- Current Month Accomplishments Versus Planned. Reflected significant activities against planned for the current reporting month.
- Next Month Planned Accomplishments. Reflected plans for significant activities during the succeeding reporting period.
- Tabulation of Controlled Milestones and Dates.
- Center Skylab Resources Summary. Reflected total center level cost and obligation, including total for all years.

Project Level 2 SARP Requirements.

- Program Manager's Evaluation. A narrative summary for highlighting all significant activities, problems, and brief status for each project. Identified present or probable

significant deviations from plans (particularly cost, schedule, manpower, or technical content) and action being taken.

- Major Problems. Program Manager's evaluation of significant problem reports included identification or definition of the problem; potential impact on overall cost, schedule, or technical performance; recommended solutions; and required actions by Centers and Headquarters.
- Project Overall Development Schedules. Overall development covered all phases of planning, management actions, key documentation, development, testing, fabrication, assembly, and checkout of ground and flight articles up to and including delivery to KSC.
- Project Resources Summary - Current Fiscal Year (FY). Curves for the current FY reflecting actual versus planned obligations and costs. Included an authority curve. Included monthly obligations and costs, planned and actual, in tabular form. Summary columns included prior years and totaled all years.

Module Level 3 SARP Requirements.

- Module Overall Development Schedules. Same requirements applied as defined for Project Overall Development Schedules in the previous paragraph.
- Module Schedule Trend. Two lines reflected the baseline plan and the management assessment. Begin with October 1968 (the first month ML-15 was issued in Level 1 SARP) and reflected delivery needs for the module as related to ML-15 schedule. Included a properly coded Manager's assessment of delivery. Included reasons for changes to plans or assessment.
- Module Resource Summary (Current FY). Same requirements applied as defined for Project Resource Summary in Project Level 2 SARP Requirements paragraph.
- Module Resource Summary (All FY). This tabulation included monthly planned and current estimates for obligations, cost, cost rate, and direct manpower for the current fiscal year and the succeeding FY.
- Module Cost Trend. Two lines reflected the current approved run-out cost and the management assessment, plotted against time beginning with October 1968.

- Module Planned Versus Actual Drawing Releases. For each module (flight hardware) included a cumulative curve (S-curve) of percent of final drawing release completed (as related to CDR), including all drawing changes, against time for planned and actual releases.
- Module Planned Versus Actual Verification Program. For each module (flight hardware) included a cumulative curve (S-curve) plotted against time for planned versus actual tests starts, and for planned versus actual test completions. Tabulations below the curves included numerical data supporting the curves.
- Module Verification Program Status by Systems. This was a schedule chart broken down by system reflecting total number of tests required for each system test program and cumulative numbers of actual completions as of the reporting date.

Systems Level 4 SARP Requirements.

- Experiment or System Development Schedules. For system schedules, each center Manager selected significant systems to report against.
- Experiment Cost and Obligation Tabulation. For each experiment for which a center had development responsibilities, tabulation of total cost and obligations for prior years, current year by month, and total cost and obligation estimate to run-out.

3. Conclusions and Recommendations. Implementation of a centralized planning and control authority, complimented by continual project level management participation in regular program review and reporting activities, provided an extremely effective information and control system.

Use of SARP techniques and Control Room displays provided a comprehensive method of presentation whereby emphasis could be focused from one program element to another as Skylab progressed through the various phases of change and development. The ability of this method to identify affected elements and potential impacts was successfully demonstrated repeatedly throughout the Skylab Program.

B. Reliability Program

1. Objective and Methods

a. Purpose. The SWS reliability program was established to influence SWS design and thereby achieve a safe environment for the crew and a secure operational capability for satisfying primary mission objectives.

b. Summary. Reliability program requirements applicable to the SWS are contained in the Cluster Requirements Specification. The following program elements were the basis for achieving desired reliability for the Skylab missions:

(1) Design Goals. Components were designed to be fail-safe. It was a design goal that no single point failures should adversely affect crew safety or prevent the attainment of primary mission objectives. The design should not be made dependent upon the development of new components or techniques when performance and reliability requirements could be met by the use of established technology. Components that were in the National Aeronautics and Space Administration inventory and were procured to Specification NHB5300.6, Parts and Material plan, were given priority consideration in the design and selection process for the Cluster System and its subsystems. Existing test data was used to the maximum extent practicable to demonstrate that such components were capable of meeting mission requirements.

(2) Reliability Analyses. Reliability analyses, which consisted basically of failure mode and effect analyses, were conducted to identify the effect of component failure on mission objectives and to categorize failure modes by criticality. All components whose failure would adversely affect crew safety or result in not achieving a primary mission objective were identified. Retention of these failure modes was rigorously justified.

Two types of Failure Modes and Effects Analysis (FMEA) were conducted to evaluate the effects of failure on equipment operation, mission objectives, and crew safety. Equipment level FMEAs were conducted to identify equipment failure modes and the consequences of failure in these modes on the performance of subsystems that were comprised of these equipments. A Mission Level FMEA was conducted to define those critical functions and related hardware that could lead to the compromise of specific mission objectives or crew/personnel safety. The Mission Level FMEA used a top-down approach and bridged the gap between equipment and mission by singling out only the critical hardware items that were truly single failure points for the mission being examined.

Both analytical techniques led to the identification and baselining of critical items through the Skylab Level II CCB. Each participating contractor prepared a retention rationale for critical

items in his equipment and developed special controls and test programs to minimize the risk of failure.

c. Methods

(1) Approach

(a) Equipment Level FMEA Critical Items List (CIL). Equipment Level FMEAs were prepared for Skylab modules and experiments. In general, these analyses began with reliability logic diagrams based on established techniques. These diagrams provided a visible tie between hardware design and analyses and displayed functional relationships among hardware elements. Both series and redundant elements were included in the diagrams. Transition between the diagrams and the FMEA was accomplished through coding systems that assigned unique numbers progressively from subsystems down through components. The FMEAs were performed on components identified in the logic diagrams in general accordance with the established format requirements. Failure modes were analyzed for their effect on the system, mission, and crew safety in each applicable mission phase. Failure detection cues available to the flight and ground crews were evaluated and failure reaction time was estimated. Recommendations were made for the resolution of critical failure effects.

A critical items list was prepared by each module contractor summarizing the results of the failure mode and effect analysis. The Single Failure Point (SFP) Summary contained a description, failure consequence, and a rationale for retention or corrective action for each SFP in Categories 1 and 2A. The Launch Critical Component Summary contained a description, failure consequence, and recommended corrective action for each component whose failure before launch would result in a launch scrub. The Critical Redundant/Backup Components Summary identified primary and backup components and described failure modes in the primary component and compensation provided by the backup component. The module CILs were maintained through SL-1 Flight Readiness Review (FRR).

(b) Mission Level FMEA/CIL. The Skylab program was divided in two phases for the purpose of defining FMEA activity, mission definition, and module and experiment design. The Mission Level FMEA was begun during the mission definition phase.

A top-down mission Functional Failure Effect Analysis (FFEA) was conducted using mission description documents to identify the sequence of major mission events. The events were subdivided in functions and subfunctions so that analysis and identification of their purpose in the mission was evident. The types of module failures that occur were identified and their effects on the mission and crew were evaluated. The identification of functions that were critical to mission success or crew safety became the baseline for a detailed analysis of hardware required to perform these functions in the Mission Level FMEA.

The Mission Level FMEA proceeded by collecting critical subfunctions from the FFEA into related or similar effect groups. In turn, these subfunctions were matched with the hardware elements necessary to perform the function. Failure modes identified in equipment contractors FMEAs were reviewed for Skylab mission implications and additional analysis was performed to assure that all critical failure modes were covered. The resulting failures were then related to common mission effects by mission phase, with particular attention given to failures that propagate across functional or hardware interfaces.

A Mission Level CIL was prepared which included Skylab flight components that were identified as mission or crew critical by the Mission Level FMEA. Components included in this list were limited to those items not included in the Module CILs that had been baselined by Level II CCB approval. The list was maintained through SL-1 FRR and contained detailed information on all candidate components that required to be disposed of and provided status of actions taken on items submitted in previous revisions of the list.

(2) Definitions

(a) The mission effect of each failure was assigned a criticality category in accordance with the following definitions:

<u>CATEGORY</u>	<u>DESCRIPTION</u>
1	Loss of life (or serious injury) of crewmember(s) (ground or flight).
1S	Applies to Safety and Hazard Monitoring Systems (C&W system). When required to function because of failure in the related primary operations system(s) potential effect of failure is loss of life of crewmember(s).
2A	Immediate mission flight termination or unscheduled termination at the next planned earth landing area. (For Skylab includes loss of primary mission objectives.)
2B	Launch scrub.
3	Launch delay (also includes loss of secondary mission objectives for Skylab).
3A	Degradation of primary mission objectives resulting from a component failure that impacts two or more group related experiments.

(b) Critical items were classified in accordance with the following definitions:

<u>CRITICAL ITEM CATEGORY</u>	<u>DESCRIPTION</u>
Critical Single Failure Point	A single item of hardware, at the component level, the failure of which will

CRITICAL ITEM CATEGORYDESCRIPTION

	lead directly to a condition described by failure categories 1, 1S, 2A, or 2B.
Critical Redundant/ Backup Component (CRBC)	A redundant component (in the same system) whose next failure would result in a condition described by failure categories 1, 1S, or 2A.
Launch Critical Component (LCC)	An item with failure modes that can result in launch scrub. Criticality category 2B, i.e., a launch delay long enough to require retanking of propellants or rescheduling the launch to a later date.
Ordnance Components	All pyrotechnic and explosive devices.

(c) The criticality of failure effects was based on crew safety and mission objectives. For hardware development the mission objectives were treated as criticality category 2. Individual ATM, Earth Resources, and Medical Experiments were considered category 3. Scientific, Engineering, Technology, and Department of Defense Experiments were classified in category 3 or 4, as specified by the development centers. Individual critical elements within an experiment were classified category 1 or 2 as appropriate.

(3) Experiment Level FMEAs. Equipment Level FMEAs on modules and experiments were prepared in accordance with contractor-prepared/NASA-approved reliability program plans. The plans controlled the scope, format, and submittal schedules for individual FMEAs. Module FMEAs were scheduled to be available at major program milestones and were used extensively for assessment of design concepts and features during inhouse reviews, formal design, and program reviews. Formal reviews began with PRR and CDRs and extended through FRR. Module FMEAs included the following:

<u>MODULE</u>	<u>AGENCY</u>
ATM	MMC/Bendix
OWS	MDAC-W
AM	MDAC-E
MDA	MMC

Module FMEAs were maintained throughout the program with major emphasis placed upon elimination of critical failure modes. Component design, workarounds, and contingency plans and procedures were the principal methods by which this was accomplished. By FRR, critical failure modes associated with each module were reduced to the quantities identified below:

CRITICAL FAILURE MODES

<u>MODULE</u>	<u>CATEGORY I</u>	<u>CATEGORY 2A</u>
OWS	10	52
MDA	2	6
AM	3	28
ATM	<u>0</u>	<u>28</u>
TOTAL	15	114

The majority of critical failure modes affecting crew safety fell into three categories: fire hazard, rupture of stored energy device, and loss of SWS pressure integrity. These components included:

<u>MODULE</u>	<u>COMPONENT</u>	<u>FAILURE MODE</u>
OWS	TACS Storage Spheres	Rupture
OWS	TACS Manifold	Rupture
OWS	M131 Pressure Vessel	Rupture
OWS	M509/T020 Pressure Vessel	Rupture
OWS	SAL Window	Structural Failure
OWS	M131 Rotating Litter Chair	Structural Failure
MDA	S190 Window	Structural Failure
MDA	S192 Window	Structural Failure
AM	Coolant Loop	Leakage/Fire Hazard
AM	N ₂ Tanks	Structural Failure
AM	O ₂ Tanks	Structural Failure

d. Design Evaluation

(1) Mission Level FMEA. The top-down FFEA, was published in November 1970. The definition of the mission by functions or events, and the analysis of these functions and all supporting functions for impact on mission and crew were contained in the FFEA. Loss of each function or subfunction was analyzed for its effect on vehicle, crew, and mission. Known redundant or backup modes were noted in the FFEA. Given that a failure had occurred, the probability of the loss affecting vehicle, crew, or mission was given in terms of possible loss (1-10%), probable loss (10-90%), and actual loss (90-100%).

The FFEA was limited to considerations of single function losses and their effects on mission and crew. Multiple function losses or interaction effects were not analyzed. There may be several ways a function can fail but the effect on the vehicle, mission, and crew reflected the "worst case" only.

A summary of critical functions identified with each Skylab mission is as follows:

<u>MISSION</u>	<u>CRITICAL FUNCTIONS</u>	
	<u>CATEGORY 1</u>	<u>CATEGORY 2A</u>
SL-1/2	87	251
SL-3	84	225
SL-4	77	129

The SL-1/2 mission was the most critical with a total of 87 potential functional failures that resulted in crew hazard and 251 that resulted in loss of primary mission objectives. The SL-3 mission was second and SL-4 mission was third. The SL-1/2 mission included functions for initial activation of the SWS, i.e., deployment of ATM and OWS solar arrays, which was not required in subsequent missions.

The most critical part of each mission from the standpoint of crew safety was the OA activation phase. The major contributing factor to crew safety in this phase was loss of electric power from power generation and distribution systems primarily in the OWS, and to a lesser degree, the power systems in the ATM.

The phase that produced most of the failures with a resulting loss of primary mission objectives was the on-orbit activity phase. The greatest single contributor to loss of mission objectives in SL-1/2, SL-3, or SL-4 was the inability to perform or complete the ATM experiments.

The importance of the FFEA in the system integration process was to highlight those mission functions whose failure would prevent successful completion of mission objectives or affect crew safety. The FFEA was a prerequisite to the Mission Level FMEA by defining the critical functions on which to perform further in-depth analysis at the hardware level.

The Mission Level FMEA was prepared and published in November 1971 and maintained through March 1973. The document consisted of a summary volume and nine appendices; electrical power, mechanical and fluid equipment, instrumentation and communications, guidance and control, C&W, medical experiments, EREP experiments, ATM experiments, and corollary experiments.

The Mission Level FMEA identified 139 components with one or more failure modes that resulted in one or more critical effects. Grouping the critical effects against four major time/activity phases of the mission indicated that 60 related to SWS activation, 45 related to manned operations-SWS systems, 71 related to manned operations-experiments, and 10 related to deactivation and storage. Successful completion of the nonrepeating functions in the first premanned operations phase (SL-1) removed 53 critical effects from consideration in subsequent missions. Critical effects (Category 1 and 2) contributed to the mission phase totals as follows:

<u>MISSION PHASE</u>	<u>CRITICAL EFFECTS</u>		<u>PHASE TOTAL</u>
	<u>CATEGORY 1</u>	<u>CATEGORY 2</u>	
SWS Activation	0	60	60
Manned Operations-SWS Systems	9	36	45
Manned Operations-Experiments	14	57	71
Deactivation and Storage	0	10	10
TOTAL	23	163	186

Recommendations were made for potential contingency or alternate operation studies for the following conditions that resulted from one or more SFPs.

- Off-nominal orbit perigee.
- No OWS Solar Array or Meteoroid Shield deployment due to loss of both deploy buses.
- Partial or total loss of ATM T/M output.
- SWS atmosphere contamination due to coolanol leakage.
- Loss of active cooling for ATM canister.
- Failure of PS to jettison.
- Unpredictable PS jettison trajectory.
- Damage/contamination to ATM and MDA due to failures in the shroud separation system.
- ATM fails to fully deploy or lock.
- Partial or no ATM Solar Array deployment.
- Loss of OWS Solar Array power.
- Failure to deploy OWS meteoroid bumper.
- Failure to vent OWS waste tank.
- Failure to close OWS habitation area vent valves.
- Open or short in TACS thruster command line during IU operation.
- Inability to dock or undock due to probe/droge failures.
- Failure to open any one of five in-line hatches during activation (CM, MDA, AM, OWS).
- Leakage in ATM C&D/EREP coolant system.
- Failure of Trash Disposal Airlock.
- Loss of ATM Experiment fine pointing due to launch lock failure.
- Loss of OA pressurization.

(2) Critical Items List

(a) Equipment Level CILs. The process of baselining Skylab critical items was implemented in accordance with the MSFC Skylab Configuration Management Manual, MM8040.10A, and MSFC Program Directive - Skylab Critical Items Control, MPD 8020.4. Project Office (AM/MDA, ATM, OWS, GSE) were assigned primary responsibility for initiating necessary actions that resulted in five baselined module CILs. The actions included an MSFC inhouse review, a preboard review, and a joint Level II CCB reviews. The MSFC Central Systems Engineering was assigned responsibility for conducting an in-depth review of each critical item to validate the accuracy and adequacy of the relevant analysis methods and the retention rationale for acceptance of the design containing the critical item. The module CILs were available, in preliminary form, at module CDRs (conducted between May and September 1970) and baselined as indicated below.

<u>MODULE CIL BASELINE</u>		
<u>MODULE</u>	<u>AGENCY</u>	<u>CIL BASELINE</u>
ATM	MSFC	September 1971
OWS	MDAC-W	June 1971
AM	MDAC-E	April 1971
MDA	MMC	May 1971

The baselined critical items were given continuing attention through the major program reviews including SOCAR, DCR, and FRR. At each review, the retention rationale for each SFP was reassessed and the potential for eliminating SFPs was reevaluated. Consideration was also given to operational workarounds and constraints, and development of launch and mission rules.

(b) Mission Level CIL. The Mission Level CIL included items overlooked by the baselined module CILs (including experiments) items that could not be identified without analysis peculiar to the Mission Level FMEA, and items identified in the Module Level FMEAs but whose criticality to 1, 1S, 2A, or 2B as determined by mission level analysis. The Mission Level CIL was initially published in May 1971 and maintained through five revisions with the final release published in February 1973.

A total of 97 critical item candidates were identified, including 2 Single Failure Points (SFP), five Launch Critical Components (LCC), and 20 Critical Redundant/Backup Components (CR/BC). All items approved by MSFC were either eliminated by redesign, proposed for addition to the various Module CILs, or added to baselined CILs by Level II CCB action. A summary of critical item candidate submittals and how they are disposed of is presented in Table V.B-1.

Table V.B-1. Critical Item Summary

<u>CRITICAL ITEM</u> <u>CATEGORY</u>	<u>ITEMS</u> <u>SUBMITTED</u>	<u>WITHDRAWN/</u> <u>DISAPPROVED</u>	<u>DEPOSITION</u>	
			<u>ELIMINATED</u> <u>BY REDESIGN</u>	<u>BASELINED</u> <u>VIA CCB</u>
SFPs	72	25	6	41
CR/BCs	20	11	0	9
LCGs	5	1	0	4

The majority of the 25 SFP candidates in Table V.B-1 were withdrawn on the basis of MSFC guidelines regarding identification of SFPs, structures and reassessment of failure effects on primary mission objectives. Eleven CR/BC candidates were withdrawn on the basis of MSFC supplemental guidelines for baselining CR/BCs.

Procedures for baselining critical item candidates contained in the Mission Level CIL were comparable to those established for baselining

Module CILs. Each critical item candidate was reviewed by MSFC Central Systems Engineering and an ECR was prepared to either

- (1) redesign and eliminate the critical item, or
- (2) accept the risk associated with the critical item but initiate action to minimize it.

In the latter situation, the ECR was written to incorporate the critical item in the baselined Module CIL.

(c) Utilization of FMEAs/CILs. The process of identifying, baselining, and controlling critical items precipitated a variety of program activities with the objective of minimizing the risk of failure occurrence. Although emphasis was placed on elimination of SFPs during the design and development phase, such action was not often feasible or practical. After initial baselining of critical items, program attention was given to the development of rigorous justification for retaining SFPs. A parallel effort was begun to provide workarounds and mitigate the potential effect of failure. For example, studies were undertaken to evaluate the pressurized SWS and critical components that could cause mission termination or present a hazard to the crew if penetrated by a meteoroid. The meteoroid vulnerability analysis considered both component criticality and location.

Validation of safety margins through test programs became the basis for retention rationale for the majority of critical items. Such tests on SWS windows included pressure tests with induced cracks, flow growth, and differential pressure tests to safety factors as high as 20. Pressure vessels were subjected to cycle, notch, and burst tests during development and qualification testing.

Contingency analyses were undertaken to define a preplanned course of action to be taken in the event of a critical failure. The Mission Level FMEA provided candidates for which contingency action was considered feasible. In a typical case, the Mission Level FMEA identified critical items that could result in inability to deploy the ATM. Subsequently, Skylab Program Contingency Analysis developed procedures and identified tools for manual deployment of the ATM.

Each critical item was evaluated as a potential candidate for in-flight maintenance. Where feasible and practical, spares and tools were provided for real-time in-orbit maintenance of the SWS. For example, tools were provided to open jammed hatches in the MDA and AM.

Critical Item Lists were used as inputs to the Mission and Launch Rule Documents. Studies were undertaken to develop launch commit/launch scrub criteria for countdown failures of components in redundant systems. These criteria were based on component criticality and the extent of available redundancy.

As a final validation of SFPs, specific test requirements were incorporated in the integrated system TCRSDs applicable to the conduct of test operations at KSC. Where practical, the integrity of each critical component was demonstrated before launch to provide confidence that the SWS was failure-free at launch.

2. Conclusions and Recommendations. The complexity and multiplicity of Skylab equipment interfaces led to a program requirement for two complementary approaches to failure modes effect analysis. These included the mission-level FMEA and the equipment-level FMEA. Primary mission objectives were defined for Skylab and became mission success criteria for the SWS. With the exception of module FMEAs, the typical equipment contractor (i.e., experiment contractor) was not in a position to assess the mission effects of failure in his equipment. The analyses were often limited to evaluation of failure effects of terms of effect on equipment performance up to a physical or functional interface. In addition, mitigating circumstances often existed in the system design such that block or functional redundancy lessened the effect of failure as measured by mission success criteria. At the module level, contractor visibility of the relationship between equipment and mission objectives improved significantly. With the exception of failure modes with effects at module interfaces, the mission and crew effects of most failures could be assessed directly by the module contractor. For these reasons, a requirement existed for a mission-level FMEA that would evaluate the system implications of each failure mode and determine the ultimate effect of failure on crew safety and mission objectives.

The mission-level FMEA, therefore, concentrated on evaluation of failure propagation across equipment interfaces, experiments, as well as modules. Failure effects were examined for impact on the integrity of the SWS, both as a platform for the conduct of experiments and as a habitable environment for the crew.

Both the mission-level FMEA and equipment-level FMEA served a common purpose; i.e., identification and control of Skylab critical items.

The following recommendations are appropriate to future manned space programs:

Functional Failure Effect Analysis should be time-phased to provide criticality classifications for equipment before contract award. This is particularly significant to component procurement where the criticality category determines the scope of the component reliability and safety programs.

Initial baselining of critical items at all equipment levels should occur at CDR to provide program visibility and implementation of controls early in the development phase. In particular, SFPs should be given attention in development test programs to demonstrate safety margins and provide a basis for retention rationale.

Numerical reliability requirements and quantitative reliability assessments were de-emphasized in Skylab. Probability assessments were limited to trade studies, comparative analysis and risk assessments on critical SFPs. The FMEA/CIL was the focal point for the Skylab reliability program and should be emphasized as a cost-effective foundation for future reliability programs on large-scale systems.

The philosophy of baselining critical items through a Level II CCB should be continued into future programs. The process of risk assessment followed by decision to accept an SFP on direct re-design is beneficial.

C. Safety

1. Introduction. The MSFC Skylab safety program evolved from preliminary studies initiated during the AAP. The basic purpose of the studies was to identify safety requirements and to plan a program for their implementation. The studies were classified in three interrelated categories, as follows:

- Program integration, i.e., overall program objectives, policy, program management requirements, and methods for hazard identification and elimination or control.
- Systems integration, i.e., technical criteria and requirements for flight and ground hardware design and operations.
- Implementation assurance, i.e., checkpoints, reviews, surveys, audits, and similar activities applicable to both program and system integration.

These preliminary studies were performed in recognition that a variety of aerospace organizations, both Government and contractors, were involved in the planning and development of the first orbital space station. The retention and application of diversified experience that had been gained by these organizations including methods and techniques that had been developed during prior programs was highly desirable. Furthermore, the cost and time required to impose new methods on organizations that had demonstrated success on previous programs might have been prohibitive and may not have served the ultimate safety objectives of the program. However, the predominant factors that were prevalent during these preliminary planning activities and greatly influenced the acceptance or rejection of prior program methods were (1) cost and (2) the requirements to make maximum use of existing hardware and documentation. The studies encompassed all aspects and connotations of the word safety as described in documentation developed by NASA, DOD agencies, and aerospace contractors. Safety was referred to in terms of a state or condition of hardware, individuals, or groups responsible for identifying and preventing unsafe conditions, an engineering discipline applied to the achievement of a safe condition, and a variety of others. The results of these studies led to the further development of the MSFC Skylab System Safety Program, which ultimately encompassed all of these aspects of safety.

2. Definition. The MSFC Skylab System Safety Program was that activity by which the combined efforts of management and all technical organizations were coordinated to provide timely identification and correction of the conditions or events that could contribute to unsafe systems failure, equipment damage, or personnel injury. This activity was effected through the total systems engineering and management process throughout all phases of the Skylab program.

3. Basic Objectives. The basic objectives of the Skylab System Safety Program were the assurance that:

- Maximum safety would be designed in the flight systems consistent with mission requirements.
- Adequate controls over identified hazards, inherent to ground support systems, equipment, and facilities, would be established by design for the protection of flight systems, GSE, and personnel.
- Minimum risk would be involved in the acceptance and use of new or hazardous materials.
- Hazards associated with manufacturing, including fabrication and assembly of flight systems, subsystems and associated GSE, would be identified and eliminated or controlled.
- Hazards associated with flight and ground system and subsystem testing, including such tests as those conducted for and in, altitude chambers, hyperbaric chambers, and neutral buoyancy facilities, would be identified and eliminated or controlled.
- All organizations involved in Skylab would be aware of and participate in a unified safety program. The basis for this objective was an underlying need to develop a systems approach to the management of safety related activities, and to increase the effectiveness of existing safety personnel through all organizations responsible for hardware development.

4. Policy. The basic policy in the MSFC Skylab Program was that system safety is an inherent function of the line disciplines, i.e., engineering, test, manufacturing, and operations, and cannot be separated from these disciplines. There was also a recognized need for separate and distinct system safety organizational elements in the MSFC Skylab Program Office, the MSFC S&E Directorate (in support of the MSFC inhouse activities), and major contractor organizations.

The role of these system safety elements was as follows:

a. To establish system safety requirements applicable to their functional area or project responsibility, i.e., overall program, project, contractor, or S&E Laboratory levels for such areas as system engineering and integration, OWS, AM, MDA, ATM, or experiments, as applicable.

b. To ensure compliance with established system safety requirements by means of formal reviews or audit of the line discipline activities.

c. To participate in special efforts such as (1) materials testing, selection, and control to reduce flammability and toxicity hazards to the crew, (2) materials testing, selection, and control to reduce contamination hazards effecting the achievement of primary mission objectives, (3) special studies and test programs to ensure the integrity of the pressurized spacecraft shell, (4) sneak circuit studies, (5) studies and tests to determine potential shock hazards to the crew, (6) studies of such areas as the biomedical experiments and related data systems to ensure that Criticality 3 failures could not have Criticality 2 effects (see Section V.B for definition of criticality categories).

d. To perform design safety analyses, operations hazard analyses, and other analytical efforts that were specified in contractor safety plans or by supplemental contract tasks whereby the primary responsibility for task implementation rested specifically with system safety specialists.

e. To perform reviews of test and operating procedures including those required for ground handling, transportation, service, maintenance, or storage of flight or flight type hardware. Formal concurrence was required for procedures which involved inherently hazardous tests or other operations which could have resulted in damage to hardware or injury to personnel.

f. To perform tracking and statusing functions as related to the disposition of major safety problems as identified in the various engineering analyses, mockup reviews, procedural reviews, milestone reviews, program baseline reviews, CCB proceedings, and similar activities.

5. Organization and Responsibility. The MSFC Skylab System Safety Organization is shown in Figure V.C-1. The basic responsibilities for implementing the MSFC Skylab System Safety Program were as follows:

a. The Manager of the Test, Reliability, Quality Assurance, and Safety Office (SL-TQ) acted as the official point of contact for all matters pertaining to the MSFC Skylab system safety function, and through his office provided the overall planning and direction for implementation of the MSFC Skylab safety effort. In addition, he managed special tasks, such as the Mission Level FMEA, and the System Safety Definition, Status, and Evaluation task.

b. The MSFC Skylab Project Managers for major modules, experiments, and GSE were responsible for ensuring that the Skylab system safety program was implemented by their contractors or the responsible MSFC S&E organizations, as appropriate.

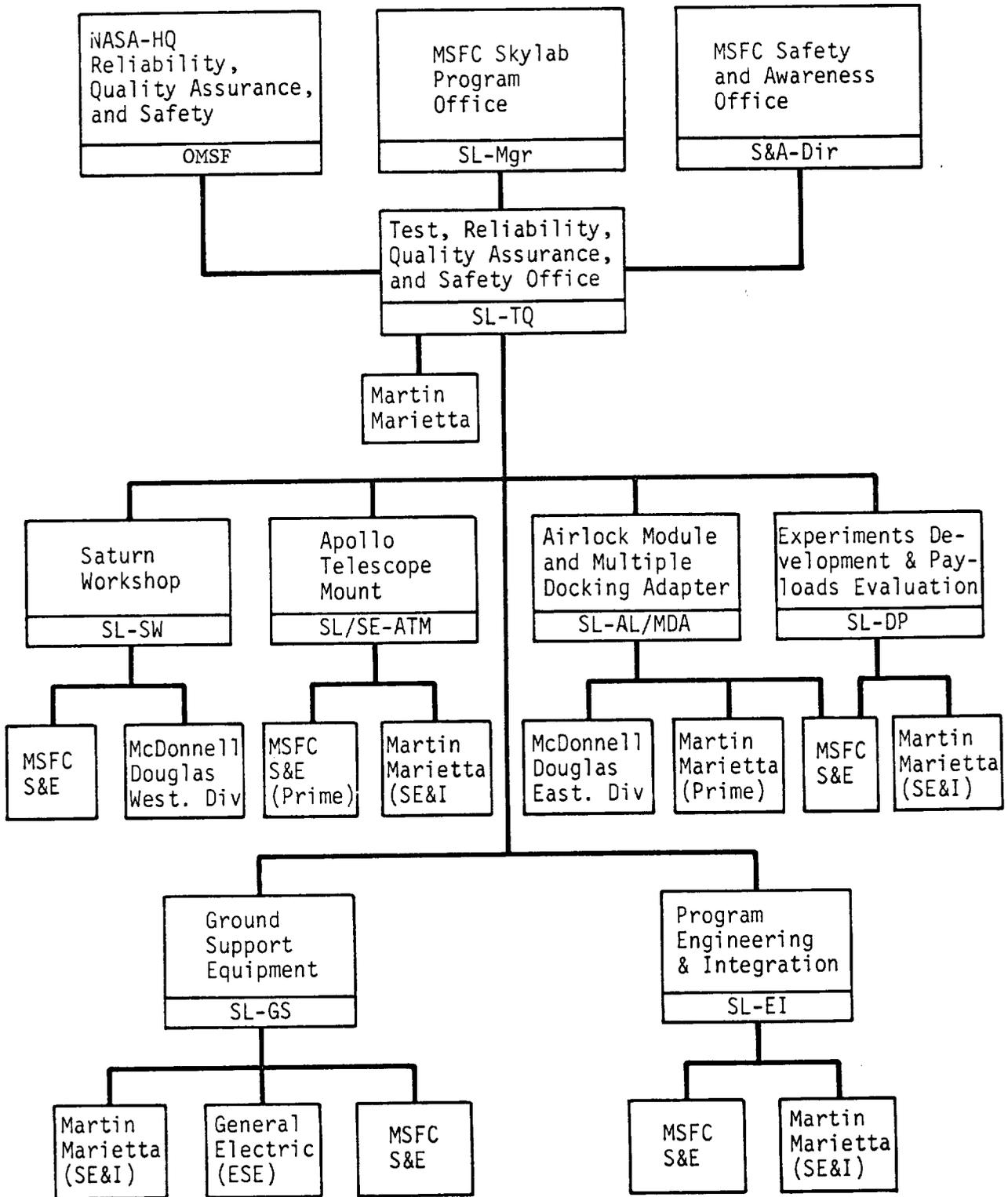


Figure V.C-1 MSFC Skylab System Safety Organization

c. The Manager of the Systems Engineering and Integration Office (SL-EI) provided engineering support to SL-TQ and the Skylab project offices, as required, in the implementation of the Skylab system safety effort.

d. MSFC S&E provided technical support to the Skylab Program Office, as required, in the implementation of the Skylab system safety effort. This effort included technical monitoring and assessments in such areas as surveys and audits, the technical review of equipment and mission level FMEAs, and the technical review of safety analyses of GSE and associated ground operations involving Skylab hardware.

6. Management and Implementation Approach. Safety representatives were assigned as focal points for coordinating all system safety activities within each project throughout the Skylab Program Office. Project offices responsible for multiple hardware systems and equipment, such as the Experiments and GSE projects, provided safety personnel in addition to contractor system safety specialists who were assigned to perform special safety tasks. All major contractors provided full-time system safety personnel as points of contact for overall safety efforts. In addition, safety specialists were assigned to such groups as engineering, reliability, and quality to implement special safety efforts specified in formal safety plans and other contractual documentation.

Similarly MSFC S&E organizations identified points of contact for safety matters in such areas as overall systems engineering and systems verification and test, including GSE. The number of personnel assigned fluctuated according to the scope and complexity of effort, and the degree of depth determined to be necessary to achieve the safety objectives or task requirements. As an example, S&E full-time safety personnel, supported by additional system safety personnel from both the integration contractor and the principal ESE contractor, were assigned to the ATM flight hardware test team, which remained with the hardware from shipment through the completion of launch operations at KSC. This organizational approach, within the framework of the previously stated policy and responsibilities, provided effective management for the achievement of overall MSFC Skylab system safety program objectives. Specifically, this approach resulted in the following:

- Provided up-to-date visibility of safety-related activities through each system safety representative who was organizationally associated with his specific program, project, and technical area of responsibility.
- Provided effective integration of overall program safety activities between project offices, MSFC S&E organizations, and contractors.

- Minimized duplication of effort through a centralized program safety organization, with specific elements identifiable with other technical disciplines, under a single system safety manager.
- Provided a central point of contact between MSFC Skylab organizations and MSFC top management, other NASA centers, and NASA Headquarters.
- Provided multidiscipline experienced personnel in support of system specialists.
- Minimized the development of large program peculiar safety organizations.
- Provided greater awareness and understanding of the functions and activities of safety personnel by the various engineering, production, and operations personnel at all organizational levels.
- Improved the effectiveness of limited number of safety personnel in achieving their specific tasks and responsibilities.

7. Hazard Reduction Criteria. Criteria for actions to eliminate or control identified hazards were, in order of precedence, as follows:

a. Design for Minimum Hazards. Inherent safety in product design was an ultimate goal. The major effort throughout the design phases was to assure inherent safety through the selection of appropriate design features, such as redundancy and increased safety factors, to minimize risk in case of material deficiencies in the assembled product of human error during manufacturing.

b. Incorporate Fail-Safe Features and Safety Devices. Known hazards inherent to the design or operational environment, which could not be eliminated through design selection, were precluded or controlled through the use of appropriate fail-safe features and safety devices as part of the system, subsystem, or equipment. The purpose of these criteria was to minimize the effects of potentially unsafe conditions in the event of a failure or the occurrence of undesired events due to environment, improper equipment use, or human error during flight and ground operations.

c. Incorporate Hazard Detection, Warning, and Corrective Action Features. These criteria were applied when it was not possible to preclude the existence of a known hazard or whenever a potential hazard was identified that could have been caused by an out-of-limit condition or failure, which could have adversely affected the safety of flight or ground hardware or personnel. Devices were employed for the timely detection of a hazardous condition to warn of an impending or out-of-tolerance condition, and to provide means to limit or control

the effects. Caution and warning signals and their application were designed to minimize the probability of incorrect signals or of improper personnel reaction to the signals. Hazards determined to be potentially catastrophic or sufficiently critical to require automatic corrective action features included manual or alternate backup capability.

d. Develop Special Operating Instructions. Precautionary instructions, notes, or warnings within procedures were developed to identify hazards associated with improper or out-of-sequence operations. Procedures were prepared in such a way as to counter identified potentially hazardous conditions for enhancement of flight and ground systems, equipment, and personnel safety. This criterion was applicable to all procedures associated with equipment fabrication and assembly (such as manufacturing processes and assembly instructions), testing, repair, maintenance, servicing, handling, transportation, packaging, and storage. Precautionary notations were included in procedures in accordance with the following general guidelines:

- Notes - information, techniques, etc., that should be emphasized.
- Caution - information, techniques, etc., that if not followed could result in damage to equipment.
- Warning - information, techniques, etc., that if not followed could result in injury or loss of life.

e. Provide Training and Certification of Personnel. These criteria were applicable to assembly, test, inspection, and operating personnel to ensure their awareness of identified residual hazards. This training was developed to familiarize personnel with design or procedural controls that had been established to minimize risk.

8. System Safety Program Implementation. The following paragraphs summarize the highlights of the overall MSFC Skylab Safety Program.

a. Safety Plans. System safety plans were prepared by all project offices or contractors, as appropriate, who were responsible for major modules and overall support equipment. Each plan, although tailored to the specific hardware and functional responsibilities of the project, contained a description of the basic requirements, responsibilities, and activities considered necessary to effectively manage the system safety program. Each plan was generally developed or updated to reflect the integrated effort within the total project and was in conformance with the basic MSFC Skylab program objectives, policy, and guidelines outlined by SL-TQ. Table V.C-1 is a composite list of elements, by subject title, that were used in developing Skylab system safety requirements. Each plan was prepared, updated, and approved through a review process as follows:

- Concurrent with initial planning efforts by project and module contractor organizations, preliminary studies and planning activities were performed by the integration contractor in support of SL-TQ. Overall planning activities performed by SL-TQ resulted in a composite summary of preliminary safety program requirements and guidelines. The principal requirements documents used as source data included NASA Headquarters Safety Program Directive No. 1, Apollo Applications Program Directive No. 31, NASA Management Instructions (NMI), Marshall Management Instructions (MMI), Kennedy Management Instructions (KMI), and the Air Force Eastern Test Range Safety Manual (AFETRM 127-1). Numerous other technical documents were studied for applicability such as ASFC DH 1-6, System Safety Design Handbook, and the Johnson Space Center developed Manned Spacecraft Criteria and Standards (MSCM 8080). These preliminary system safety program requirements and guidelines were updated and implemented, as appropriate, throughout the Skylab program as new revisions to NMIs, MMIs, and similar documents that directly applied to Skylab were issued.

Table V.C-1. Skylab System Safety Program Elements

System Safety Plans
Management and Control
- Policy and Procedures
- Responsibility
- Organization
- Safety Interface with other Program Functions
- Integration
Safety Documentation
- Standards
- Policy and Procedures
- Specifications and Manuals
Safety Hazard Analyses
- Equipment and Mission Level FMEAs
- Flight Systems Design
- Ground Support Equipment and Facilities Design
- Crew and Mission Operations
- Ground Operations and Tests
Hazard Elimination and Control
Safety Design Criteria and Requirements
Hazard Data, Collection, Analysis, and Corrective Action
Safety Milestones and Schedule

Table V.C-1. Skylab System Safety Program Elements (cont'd)

Safety Input and Participation in Major Program Milestone Reviews

Test Program Safety Requirements and Constraints

Special Safety Tests

Review of Changes

- Design
- Plans and Schedules
- Procedures

Review and Status of Deviation and Waivers

Training Program

- Training
- Certification
- Flight Crews (Hardware, Data and other Support to JSC)
- Mission Support Crews
- Test and Ground Operations Crews

Industrial and Public Safety

Accident and Mishap Investigation and Reporting

Failure and Anomaly Reporting and Corrective Action

Safety Monitoring and Surveillance

Safety Surveys and Audit

Human Engineering

Range and Pad Safety

Handling, Transportation and Storage

- Equipment
- Operations

Hazardous Materials and Commodities

Safety During Manufacturing and Assembly

Selection and Procurement of Parts and Materials

Safety Reviews and Inputs to Procedures

- Tests and Hazardous Operations
- Maintenance
- Handling, Transportation and Storage

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Table V.C-1. Skylab System Safety Program Elements (cont'd)

Contingency and Emergency Plans and Procedures
- Mission and Flight Crew Operations
- Emergency and Equipment Safing Procedures during Tests
Requirements to Provide
- Critical Components Lists
- Single Failure Points Lists
- Potentially Hazardous Items and Operations Lists
Emergency and Warning Systems
- Flight (Caution and Warning)
- Ground (Hazard Detection and Damage Control)
Safety Awareness and Motivation

- Upon completion of project and contractor formal planning activities a series of reviews, surveys, and coordination visits were conducted. This activity, initiated by SL-TQ, included representatives from SL-TQ, the integration contractor, and the respective module project and contractor organizations. The meetings resulted in an assessment of module level planning activities, a better understanding by all organizations involved as to the scope and depth of planning required by the MSFC Skylab Program Office, and an understanding of the differences between the various organizations and methods for implementing the safety program. Subsequently, contractor preliminary safety plans were updated, efforts to further develop safety program plans were initiated within MSFC for inhouse work, and the composite list of system safety program elements was updated, baselined, and used as guidelines for overall management of the Skylab system safety effort. As an example, this composite list, the scope of which varied between projects, was used for subsequent status reviews through the issuance of a status matrix by SL-TQ to each project for completion and return (self assessment technique), and for the development of a combined Reliability, Quality Assurance, and System Safety Survey Checklist. The latter effort was performed jointly by the MSFC S&E Quality Laboratory and SL-TQ. The system safety input to this checklist document was developed by the integration contractor, and the overall document was reviewed and approved for Skylab application by SL-TQ. Subsequently, using these checklists, MSFC S&E performed formal surveys and audits of Skylab organizations and their activities.

b. Experiment Project. Because of the varying numbers and complexity of experiments, and the dual responsibility of MSFC for overall payload integration of experiments in addition to prime responsibility for the development of selected experiment hardware, a separate approach was taken for planning and implementing the system safety

program, and is outlined as follows:

(1) A safety review team was established consisting of members of SL-TQ, the integration contractor system safety group, the MSFC experiments project office, MSFC S&E, and support contractor safety representatives.

(2) An assessment was made of each experiment for which MSFC had prime development responsibility. The assessment was made to determine the necessary analyses and other safety-related activities that would be required to meet the overall safety program objectives. The criteria applied were the same as for the major modules. The nature (active or passive), operating environment (preflight, postflight, and flight, including module location), and complexity of each experiment were considered. Materials compatibility, contamination of other experiments or equipment because of outgassing or venting, crew operating conditions, and similar aspects were considered. As a result of these assessments specific efforts were performed for MSFC responsible experiments. These efforts are described within the appropriate paragraphs throughout this document. For this reason, specific MSFC experiment efforts are not treated in detail within this paragraph.

(3) An assessment was made of all other experiments for which other NASA centers and Government agencies had prime development responsibility. The assessment initially consisted of a review to determine whether an FMEA, hazard analysis, or other assessment had been performed. On completion of this review a determination was made as to which experiments required additional safety reviews, FMEAs, or analyses. The safety review of the status of activities performed by other centers and Government agencies included representatives of these organizations.

(4) In addition to the preceding activities described, an overall experiments systems engineering and integration compatibility assessment was performed as a separate effort by the integration contractor in support of the MSFC Experiments Project Office. Safety was a specific subject treated in monthly status reports. This activity was coordinated between the integration contractor organizations performing both the Mission Level FMEA and the overall System Safety Definition, Status, and Evaluation task in support of MSFC SL-TQ.

(5) The major program design reviews were also used to address potential problems which required additional attention. Review Item Discrepancies were submitted for potential problems and required formal review and disposition.

(6) Module contractors also performed a variety of assessments for experiments to be performed, stored, or service within the major modules for which they were responsible. As an example, JSC

was responsible for development of the M509 Astronaut Maneuvering Unit. The equipment was stored and flown within the OWS, for which MSFC had development responsibility. The inflight servicing of the 3000-psi nitrogen bottles used for M509 propulsion was performed in the AM, which was also an MSFC responsibility. Typical activities that were performed for the M509 were as follows:

- Fracture mechanics design criteria were applied to the 3000-psi pressure vessels used for propulsion.
- Design safety analysis of the overall M509 as a system was performed under the prime contract with JSC.
- Studies were performed to determine OWS equipment susceptible to impact by the M509 during flight operations.
- FMEAs were performed for the M509 system.
- M509 velocity studies were performed to determine potential damage to equipment susceptible to impact during flight operations and in consideration of failure modes identified by FMEAs.
- Safety assessments were performed by MSFC organizations and contractors for the various FMEAs, safety studies, velocity studies, OWS equipment impact susceptibility studies, and potential problems identified.
- An onsite inspection and review of high fidelity trainer at JSC was performed by integration contractor system safety personnel in support of SL-TQ. The effort was performed as a final assessment after review of data resulting from the first six items above and in preparation for the DCR. The effort was performed in conjunction with a status review and assessment of a number of other experiments, and was coordinated between JSC safety personnel and the MSFC Experiments Project Office, MSFC S&E, and their support contractor safety personnel.

(7) Other experiment safety assessment activities, which were the primary development responsibility of JSC, and which were similarly coordinated by MSFC and its contractors, include:

- M092 Inflight Lower Body Negative Pressure
- M093 Vectorcardiogram

- M133 Sleep Monitoring
- M171 Metabolic Activity
- M509 Astronaut Maneuvering Unit Simulations
- S063 Ultraviolet Airglow Horizon Photography
- T025 Coronagraph Contamination Measurement
- Operational Biological Instrumentation System
- Earth Resources Experiment Package

c. Hazard Analysis and Related Hazard Identification Efforts. Initially, the fundamental analytical tools of the MSFC Skylab System Safety Program were the equipment FMEAs (including major modules) and the Mission Level FMEA (MLFMEA). Periodic management reviews, milestone reviews, and other assessment activities that were progressively performed indicated that many aspects or activities of the Skylab program would not be adequately covered by the FMEAs. Therefore, special efforts were implemented to assess such aspects or activities satisfactorily. Some of the more significant of these special efforts are described in the following paragraphs as well as a brief discussion of the MLFMEA relative to the system safety objectives and organizational involvement.

(1) Mission and Equipment Level FMEAs and SFP Control. Mission level and equipment level FMEAs were performed for all Skylab flight and flight support equipment in accordance with the requirements of Apollo Applications Program Directive No. 13. The SFP information provided by these efforts was included in each major Skylab milestone review. All SFPs were carefully analyzed for their impact on crew safety and the accomplishment of primary mission objectives. ALL SFPs were analyzed for possible elimination and where elimination was not possible or practical, a rationale for retention was developed. Critical Items Lists were developed, baselined, and controlled in accordance with MSFC MPD 8020.4. In addition, all critical SFPs (Categories 1 and 2) required increased emphasis on test, quality, inspection, and tracking activities.

The MLFMEA assessed the various module and equipment level FMEAs in addition to identifying and assessing failure modes affecting other modules and the overall cluster (See Section V.B for details). Integration contractor personnel from systems engineering, reliability, human factors, and system safety organizations were selected and organized in single, integrated MLFMEA team assigned to perform the analysis. Systems level groups, such as electrical power, structural and mechanical, thermal and environmental control, and experiments, were established. Each of these groups consisted of a multidiscipline team having appropriate technical backgrounds and experience in the fields of reliability,

system safety, etc. The team concept, the safety methods, and specialized techniques developed during previous programs were all in evidence in the planning and implementation of the MLFMEA. Thus, the MSFC system safety objectives, policy, and organizational approach for implementing the overall system safety program were maintained. The MSFC Test, Reliability, Quality Assurance, and Safety Office (SL-TQ) was responsible for overall management of the MLFMEA.

(2) Design Safety Analyses and Assessments. Preliminary and detail design safety analyses or assessments were performed for selected systems, subsystems, and GSE that were determined inherently hazardous or considered critical to the achievement of primary mission objectives. Various methods were employed in the performance of these analyses and assessments according to the degree of complexity, existing methods most familiar to the organization responsible for performing the analysis, judgments as to the degree of risk based on preliminary reviews, and similar factors. In all cases the analyses and assessments were reviewed by the responsible contractor organizations, the appropriate MSFC module, experiments, or GSE project offices, and SL-EI or SL-TQ, or both. Examples of such efforts are as follows:

- Multiple Docking Adapter Design Safety Analysis.
- M512 Hazards Analysis (Materials Processing in Space Facility).
- Multiple Docking Adapter Test and Operations Hazards Analysis (KSC prelaunch test and checkout and AM/MDA St. Louis operations, including Altitude Chamber Tests).
- M518 Safety Analysis and Assessment (Multipurpose Electric Furnace used with M512).
- S230 Magnetospheric Particle Composition Experiment Safety Assessment.
- T027 Contamination Measurement Sample Array and Photometer Safety Assessment.
- Airlock Module Hazard Identification (Hazard Identification Summary).
- Caution and Warning System Integration and Analysis.
- ATM Hazards Analysis of Ground Support Equipment, Facilities, Ground Operations, and Tests.

The preceding examples were specifically performed by full-time system safety personnel. In addition, numerous safety-related studies and analyses were performed by the responsible design organizations.

(3) Sneak Circuit Analysis. This effort was initiated in early 1971 and continued through final preparations for the FRR. This computer-aided special analysis was performed to identify, document, and resolve all electrical circuit latent paths that could have caused an undesired function, or inhibited a desired function, without regard to component failure. The sneak circuit analysis task is described in greater detail in Section II.F of this report.

(4) Materials Compatibility, Flammability, and Toxicity Control. The basic criteria governing material use in all crew volumes of MSFC Skylab modules were defined in MSFC-SPEC-101A. Compliance visibility and assessments were generally provided by the following methods.

- Materials lists were submitted by hardware development organizations.
- A Materials Application Evaluation Board (MAEB) was established to provide formal control of deviation requests. The MAEB consisted of representatives from MSFC Skylab program management, MSFC-S&E technical organizations, and, as required, other technical support organizations.
- The MAEB notified the design elements and appropriate MSFC project managers of approval or disapproval of deviation requests, including rationale and substantiating data, or requirements for further assessments. The MSFC or contractor design elements could appeal any disapproved deviation request through the appropriate MSFC Skylab project manager.
- MAEB activities included an active exchange of information with JSC and other sources. The information exchange included (1) maintenance and use of microfilm records of JSC materials and configuration test data, (2) daily contact with JSC and White Sands Test Facility (WSTF) materials experts, (3) MSFC collaborating with JSC on review of experiments, and (4) the exchange of approved deviation requests between MSFC and JSC.

(5) Fire Hazard Control. Through the extensive materials selection, review, and control process, the potential for fire was extremely low. Nevertheless, special significance was placed on ensuring adequate means for the timely detection, identification, and control of fire in the event of its occurrence. All potentially flammable materials stored or used in Skylab, including film, documents, similar paper products, and other combustible materials were protected by stowage provisions. Special studies and analyses were performed to identify and map the location of combustible materials. Special design features minimized the potential for propagation of fire in the event of electrical component failure, overheating due to mechanical failures (including friction), and similar potential ignition sources.

Ultraviolet detectors, as part of the C&W system, provided detection capability throughout all habitable areas of Skylab. Automatic alarms having special tones to indicate an emergency classification requiring immediate crew response were included. Fire suppression was provided by hand-held extinguishers having greater capacity than those previously used on Apollo. Extinguishers were located along escape routes for all anticipated operating conditions. Additional suppression capability was provided by the installation of a fire hose for use with reserve water supply tanks. Special safety studies and tests were performed to verify the various designs. These studies and tests considered the reaction with fire of pressurant used within extinguishers, type of nozzles used and area of coverage provided by extinguishing methods in zero-g toxicity controls for the protection of the crew, and many other factors.

(6) Meteoroid Vulnerability Analysis - The effort was performed to determine the probability of meteoroid penetration for all modules and components, such as, module pressure shells and ATM experiments, and to insure that protective shields would prevent meteoroid penetration. The evaluation of all cluster modules was performed using the same parameters and assumptions for each module. The general approach taken was as follows:

- A series of computer programs were developed and used to assess the meteoroid vulnerability of Skylab. Considerations were given to such factors as the geometric shape of the structure, material and thickness, shielding of adjacent modules, and type of shield used to protect the basic shell.
- The analysis considered the path of rays from space to the module pressure shells through adjacent protective shields by using inputs for the standard meteoroid environment defined in MSFC-TMX-53957.
- All SFPs outside the pressure shells that could have caused mission termination or create a crew hazard were identified and analyzed. Vulnerable components were tested to determine actual vulnerability when analysis indicated possible problems. Additional localized shielding was used, if necessary, to solve these problems.

(7) Electromagnetic Compatibility. A formal program was developed to insure that no adverse electromagnetic interactions would occur between Skylab systems, subsystems, and experiments. Requirements were defined in the CRS and EMC control and test plans were developed. EMC requirements and controls were inherent in the achievement of overall reliability and system safety requirements and objectives. The system safety aspects of EMC requirements and controls included protection against system degradation, unintentional initiation of circuit functions, false indications and similar potentially hazardous conditions. Electromagnetic interactions (along

wiring or radiated through space) were also closely associated with other special efforts in the areas of fault current protection, lightning, and electroshock protection.

Requirements implementation and assurance activities were keyed to Skylab hardware development and test phases. EMC was a subject during design reviews, and was considered during the development of systems specifications and drawings. Circuit development tests included preliminary interference and susceptibility checks. Overall design development tests and evaluations included considerations for shielding, wire routing, bonding, and component location. EMC was considered during qualification testing at the black box and subsystem levels. Electrical and electronic EMC testing was performed at the systems, module, and multimodule levels. Interface verifications and EMC-integrated systems tests were performed at KSC.

An EMC review board was established in 1971 to progressively review the results of EMC testing in each module. This review board was comprised of members from MSFC, JSC, and all major module contractors.

EMC critical circuit reviews were performed for circuits susceptible to electromagnetic interference that could cause loss of life, mission abort, or loss of primary mission objectives. The reviews included the IU and the CSM interface circuits with Skylab. Selection of such circuits was based on module tests of critical equipment. Insensitive circuits (relays and switches) and redundant circuits were excluded. The selection of circuits was approved and included in module test plans and controlled by the EMC Control Plan.

(8) Fault Current and Circuit Protection. The Skylab circuit protection philosophy was that all positive polarity lines of the dc distribution wiring be protected by circuit breakers or fuses. Physical protection was the method for preventing faults from occurring between the power source and first line protection.

In June 1970 an electrical intercenter panel completed a special study to determine cluster fault current design requirements. Subsequently, the intercenter panel performed reviews that included (1) the effects of opening one circuit protection device in parallel with others, (2) the adequacy of circuit protection devices relative to current, temperature, and time delay, and (3) wire size and insulation versus protective devices.

An intercenter fault current review team was also established to ensure that sufficient protection existed. The reviews included representatives from MSFC, JSC, all major contractors, and several major subcontractors. The series of surveys and reviews, including site inspections of hardware, continued through the middle of 1972.

These surveys and reviews included (a) routing of wiring, bus potting, protective coverings, insulation, clamping, bend radius, tension on cables, connectors, and terminations, (b) design and manufacturing techniques, processes, installation, and test procedures, (c) potential cable cross-connection, and (d) existence of physical protection from abrasion and chafing from sharp edges.

Additional reviews were performed as part of the Skylab System Safety Checklist Program, which is described in V.C.9. These evaluated branch circuit protection, circuit breaker and fuse sizing, current-time relationships between primary bus breakers and secondary devices. Also evaluated were (a) wire routing for protection against sharp corners and edges, (b) support, clamping, shielding, and enclosures for protection against abrasion, chafing, heat, and cold, and (c) twisting rather than bending across points of relative motion.

(9) Lightning Protection. A special review was initiated in August 1971 to (a) identify and assess the requirements that were used to implement lightning protection for all modules and experiments, (b) assess methods and techniques used to implement applicable requirements, and (c) define module and experiment retest requirements to verify vulnerable components, check electronic systems, and establish complete system confidence in the event of a lightning strike on the mated configuration of Skylab and its launch vehicle during roll-out and pad operations.

Requirements specified in MIL-B-5087B (Bonding, Electrical, and Lightning Protection, for Aerospace Systems) were used as criteria as specified in EMC control plans. Data from Apollo experience were coordinated between MSFC and JSC, and all module review reports from MSFC were forwarded to JSC in February 1972. The reviews included an assessment of module interfaces, protrusions, attachment points, truss assemblies, doors, covers, panels, electrical raceways, and GSE. The findings concluded that bonding requirements implemented on Skylab met or exceeded those specified in MIL-B-5087B (Class L-Lightning Protection). Additional protection for the modules was provided by the PS, which was considered a homogeneous counterpoise or ground plane of negligible impedance by design, thus, permitting lightning to be distributed over the entire skin surface. Further, and in addition to, conductive treatment of the PS and FAS, four aluminum bonding straps were used between the PS and FAS. The cross-sectional area of the straps was equivalent to twelve No. 10 American Wire Gauge (AWG) aluminum wires (6 times greater than required by MIL-B-5087B). The GSE was protected by being housed within the framework of the Launch Umbilical Tower. The OWS was a modified S-IVB stage and was capable of withstanding a direct lightning strike without structural damage other than surface burning. All additional OWS equipment (meteoroid shield, solar array fairing, wire tunnels, etc.) was bonded and tested.

Skylab components were vulnerable to induced currents as a result of current flow through the structure. The size of the strike, point of the strike, and duration were influencing factors. For these potential

conditions, retest requirements were defined and incorporated into the TCRSD. Skylab sustained multiple strikes at KSC. Retests revealed no significant adverse effects.

(10) Electroshock Protection. A special review was initiated in August 1971 to (a) determine the adequacy of protection available to the flight crew from hazards associated with electrical shock from powered equipment, including fault current producing failures, and static charge buildup, (b) identify design criteria and requirements imposed and implemented for modules and experiments, and (c) review MSFC and contractor efforts to ensure implementation of applicable requirements for shock protection and static buildup.

Systems safety checklist efforts for flight systems, experiments, and GSE included an assessment of electrical equipment design for protection against shock and static charges during equipment operation, maintenance, and servicing, and is described in V.C.9.

Electrical shock and static buildup was a special subject reviewed during electrical segments of the SOCAR.

Bonding requirements were specified in the CRS, module CEI specifications, and module EMC control plans. Bonding requirements for protection against shock hazards (Class H), for exposed conductive frames or for parts of electrical or electronic equipment, specified that resistance to structure be less than 0.1 ohm. Class C bonding (static charge) requirements, for internal or external isolated conductive items (except antennas), which were subject to frictional charging, specified that resistance to structure be less than 1.0 ohm. Bonding methods were as follows:

- Class H bonding (shock protection) was achieved by (a) chemically treated metal-to-metal faying surfaces between equipment cases and structure, (b) installation of metal bonding straps between equipment cases and structure, (c) installation of ground wires between equipment cases and structure brought out through individual connector pins, and (d) inherent bonding through welds or rivets.
- Class C bonding (static charge) protection was achieved by metal-to-metal contact unless development tests (resistance measurements) indicated that additional bonding was required. Processes specified preparations of surfaces.

Compliance verification of all bonding was achieved by (a) review of installation drawings and detail electrical schematics, (b) hardware inspection by quality assurance personnel to ensure conformance with drawings, process specifications, and installation instructions, (c) physical hardware inspections through the use of system safety checklists, and (d) bonding acceptance tests. Through these methods, discrepancies were identified and corrected.

(11) Corona Survey and Analysis. The effort was performed to determine which systems and experiment hardware were susceptible to arcing due to ionization of gas between conductors. Considerations were given to (a) peak and sustained operating voltages, pressures, and atmospheres, (b) outgassing port areas, outgassing products, and residual and contaminating atmospheres, both within and near each item investigated, and (c) spacing between conductors and conductive surfaces. The approach taken was as follows:

- All low voltage (less than 150 volts peak) equipment was reviewed to verify existence of at least 0.010 inch of insulation to ensure no voltage breakdown would occur.
- Above 150 volts peak, insulation was evaluated for operating life with respect to dielectric strength, temperature, homogeneity, and field stresses induced by surge, static, peak, normal, and abnormal voltage between conductors and between a conductor and a ground plane.
- Susceptible hardware was qualified by several methods, including previous flight experience, special analysis, and laboratory tests.

Reviews began in early 1971 and involved representatives of MSFC, NASA Headquarters, JSC, the integration contractor, and a number of hardware and support contractor organizations. Over 435 items of equipment were reviewed for corona susceptibility. Fifty items were found to be susceptible, six of which were duplicate pieces of equipment. Three hardware changes were made.

(12) Radiation. A series of surveys, analyses, and reviews was performed to determine the effects of the total radiation environment on Skylab components, materials, sensors, measurements, and the crew. Radiation dose limits were established for the crew by JSC Medical Operations. A radiation hazard analysis, based on the planned mission, was performed by the integration contractor. This analysis included (a) use of the GSFC (Dr. Vette) proton and electron environment models (February 1970), and (b) a 56-day mission, including consideration for planned EVA excursions (3 hours each) and the maximum number of encounters with the electron and proton belts. The analysis concluded that the maximum expected total radiation dose for the crew was well within JSC-established limits.

An analysis was also performed to determine effects on equipment (included onboard sources). The analysis considered classes of components and specific components for a 240-day period, including photographic film, optical glass, solar cells, TV camera, magnetic tapes, semiconductor devices, quartz crystal, organic materials, photomultiplier tubes, and infrared detectors. The effort initially concluded that space radiation sources might affect organic materials outside Skylab, and that photomultiplier tubes and infrared detectors of experiments T027/S073,

T003, S101, and S192, might be affected by radiation-induced noise. After additional analysis and tests, actions were completed that included installation of film vaults, removable shields over external windows used by experiments, and addition of appropriate procedural controls. It was concluded that potential residual effects would be negligible.

Detailed procedures for the safe control and handling of radioactive materials in compliance with NASA safety requirements were developed by MSFC and each of the responsible Skylab contractors. MSFC conducted a continuing survey of all radiation sources on Skylab flight and GSE hardware for which MSFC was responsible. For each radiation source, the survey identified the isotope involved and the level of radiation. With this information together with similar data compiled by JSC for their hardware, a composite listing of all radiation sources for Skylab flight hardware was assembled by JSC. The composite listing was included in the Operational Data Book and was submitted to NASA Headquarters.

(13) Microbial Control. A Skylab microbial contamination control intercenter working group was established in late 1970. The membership represented both scientific (medicine, microbiology, chemistry) and engineering (systems, materials) disciplines as well as the program offices and astronaut office. Their purpose was to perform the following:

- Identify all sources of microbial contaminants.
- Determine specific microbial (both bacterial and fungal) contaminants that would occur in the habitat.
- Determine acceptable levels after a 28-day mission.
- Establish control methods and techniques.
- Establish test specifications for all microbial testing; review test plans and monitor tests as necessary. Flight qualifications of shower, and urine centrifugal separator, are examples.
- Collect data, specify tests, and act as necessary to select and qualify cleansing agents.
- Ensure that proper housekeeping measures were included in the flight plan.
- Define sampling intervals and procedures.
- Serve as consultants for microbial contamination problems.

Microbial testing was performed on all pertinent hardware. Control methods were derived for all microbial problems identified. Betadine was selected as the biocide and packaging methods were defined. Housekeeping procedures were developed. The working group coordinated the location of onboard microbial sampling sites, supported the Systems/Operations Compatibility Review and SMEAT activities at JSC, and provided continuous monitoring of all activities which may have affected microbial control. Table V.C-2 is a summary of Skylab onboard control measures.

Table V.C-2. Onboard Control Measures

WATER

Iodine injection as required - sampling by crew.
Sample and reagent solution emptied into waste sample container.

FOOD

Housekeeping procedures.
Microbiological inspections made on food supply.
Crushed waste food cans (manual crusher) and beverage dispensers put in waste cans - dumped daily through trash airlock.
- Contingency stowage in empty freezer if trash airlock disabled.
Eating utensils and serving trays cleaned with disinfectant pads, (Zephirin - milder than Betadine) and dried with utility wipe.

WASTE

Effluent air carried through system containing microbial impingement surfaces.
- Hydrophobic membranes in fecal bag, urine separator, and fecal collector filter.
- Chiller in urine drawer inhibits growth of micro-organisms.
Water content removed from feces and vomitus in processor to inactivate (suspend) microorganisms.
Contingency procedures for maintenance and provision for spare subassemblies.

THERMAL AND VENTILATION

Debris on screens vacuum cleaned every 7 days.
Charcoal filter replaced every 28 days.

GENERAL HOUSEKEEPING

General housekeeping for spillage or contamination due to contingencies, or malfunctions.
Inside of trash airlock surfaces cleaned with Biocide (Betadine) pads.
Biocide pads (prepackaged with proper amount of Betadine) used for surface cleaning.

PERSONAL HYGIENE

Washcloth squeezer surfaces silver plated to minimize bacterial growth.
Squeezer solutions dumped from condensate bag into dump line every 48 hours.
- Condensate dump line contained Biocide (Roccal)
- Wash water dump system filter changed every 28 days.
Whole Body Shower
- Vacuum body and enclosure to pick up excess water before lowering curtain.
- Final drying with towel (body and enclosure)
- Collection bag removed and disposed through trash airlock
- Hydrophobic filter checked and replaced each week (more often if required)
- Betadine decontamination of suction head, hose, filter, etc.
- Air drying of curtain before stowage.

Table V.C-2. (continued)

SUIT DRYING

Moisture removed (minimum 90% removed).

Suit stowed in closed condition with dessicants (maintain maximum relative humidity of 55%).

(14) Protection of Glass and Other Shatterable Material. An analysis was made of all glass in windows and experiments. The JSC data, including data obtained from the National Bureau of Standards, was used. Proof test requirements were reviewed, and in some cases adjusted and thermal cycling, pressure, and impact tests were performed. Analyses and tests also were performed for mounting frames, mechanical shock provisions, seals, and similar components both individually and as complete assemblies.

Contractors and S&E laboratories performed a glass survey in late 1971 that included a JSC request to determine the existence of any structural problems. The MSFC materials division also included in the materials review program, glass and similar material subject to fragmentation.

Concurrent with the meter glass survey, system safety checklist assessments were being performed by all contractors, and for certain experiments and ATM hardware, by elements of MSFC S&E. All items, including view ports, cathode ray tubes, lighting fixtures, camera lenses, and similar components, were assessed. Discrepancies were found in LM type meters and similar previous flight qualified glass components and in some items peculiar to Skylab. Many were covered with clear pressure sensitive Teflon material.

Subsequently, and as part of the special reviews described herein, items that were still open were reaccessed. A general approach was taken to cover all remaining items susceptible to breakage with pressure sensitive transparent type material unless optical quality was a significant factor. In these cases other precautions were taken or a thorough review and justification was provided for risk acceptance. As an example, the camera port on the M512 (Materials Processing in Space) facility chamber was identified as a potential hazard through system safety checklist efforts. During the MSFC Activation Sequence/Critical Mechanisms Review a supplemental analysis was performed of the M512 chamber versus the operational conditions that would exist during the performance of all planned experiments that required the use of the chamber. Figure V.C-2 summarizes the experiments and operational conditions. Some of the other factors that were considered are summarized as follows:

- Camera port glass was not protected.
- M512 chamber was to be unattended for long periods of time.
- Break could have resulted in rapid decompression of Skylab under certain experiments operations (greatest risks were M552, M555, and M518).

SKYLAB ACTIVATION SEQUENCE/CRITICAL MECHANISMS REVIEW

EXPERIMENT	CHAMBER ATMOSPHERE	CREW LOCATION	CAMERA REQUIRED	TIMES OPERATED	OPERATING TIME (HR)	TOTAL TIME (HR)
M551(1)	Vacuum	Attended	Yes	NA	NA	NA
M552(2)	1-Vacuum 3-Atmosphere	Unattended (Cooldown)	No	4	2.75	11
M553(1)	Vacuum	Attended	Yes	NA	NA	NA
M555(2)	Vacuum	Unattended	No	1	124 (Cooldown)	124
M479(3)	Atmosphere	Attended	Yes	37 (10)*	---	10
M518(2)	Vacuum	Unattended	No	11	20 to 45	220 to 495

<p><u>Note:</u> (1) <u>Minimum Risk</u></p> <ul style="list-style-type: none"> - Attended - Camera Required - Vacuum - Rapid Crew Response - Capability to Close Vent 	<p>(2) <u>Potential Hazard</u></p> <ul style="list-style-type: none"> - Not Attended - No Camera - Vacuum - Slow Crew Response - Decompression Rate Approx 0.1 psi/min 	<p>(3) <u>Potential Hazard</u></p> <ul style="list-style-type: none"> - Attended - Camera Required - Atmosphere - Rapid Crew Response - Capability to Open Vent - Products of Combustion May Be Toxic
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*Five samples of Polyurethane and five samples of Teflon.

Figure V.C-2 Experiments Performed in M512 Chamber vs Operational Conditions

- Vent valves were to be in OPEN or VENT position during experiment operations requiring vacuum.
- Decompression rate through valves would have been sufficient to trigger the emergency alarm (Cluster C&W System, Rapid Differential Pressure Sensor).
- Camera port was a SFP (single panel).
- Inadvertent break during launch could have contaminated the cabin atmosphere (crew hazard).
- A cover might prevent loss of many experiments in the event of glass breakage (equipment hazard - many required vacuum and no camera).

The following actions were then taken after MSFC S&E and Program Office reviews: (a) a specially designed metal cover was provided by S&E to protect and seal the camera port when the camera was not in use, (b) procedures were changed to require the cover be used when the camera was not in use, (c) procedures were changed to require that the cover be installed before launch, and (d) stowage provisions were included to ensure that the cover was immediately available at the M512 work station during orbital operations.

(15) Battery Studies and Protection. A survey was performed to identify and assess the hazards associated with Skylab batteries. The effort was coordinated between MSFC, JSC, and major contractors. All batteries, both within and outside habitable areas of the spacecraft, were assessed for adequacy of protection against explosion, flammability, toxicity, and contamination (outgassing, leakage, etc.). All anticipated environments and operational conditions were considered, such as vehicle attitudes, the effects of zero-g on the type of electrolyte, and temperatures at various operational locations (including stowage of replaceable type batteries). These efforts resulted in the development of special design features and the performance of special tests to verify the adequacy of the designs. Examples are (a) relief protection for individual cells and outer containers, (b) burst tests of cell cases and containers, (c) special features to prevent the escape of liquid electrolyte through vents or relief devices in zero-g, (d) circuit protection in the event of short circuits, (e) automatic warning signals in the event of elevated temperatures and automatic disconnect of battery circuits as a backup in event of continued rise in temperature, and (f) automatic termination of charging action in event of further pressure buildup.

(16) Pressure Vessels and Fracture Mechanics Analysis. A survey was performed to identify all pressure vessels for which MSFC was responsible, including those of experiments. A review was performed to identify each vessel, defined as a container for compressed fluid that could release more than the equivalent of 0.01 pound of Tri-nitro Toluene (TNT) based on the adiabatic expansion of a perfect gas to ambient conditions. A listing of all vessels, along with appropriate configuration, analysis, and test data was compiled. The MSFC and its contractors performed a fracture mechanics analysis of all such vessels identified.

Additional testing was performed to obtain unavailable data when required. In the interest of crew safety the results were submitted to JSC for inclusion in a single listing of all hazardous pressure vessels.

9. Implementation Assurance. Periodic surveys and audits, including joint MSFC and prime contractor surveys and audits of subcontractors, vendors, and suppliers, were performed. In addition to these and other activities briefly discussed in preceding paragraphs, a number of special assurance reviews and assessments were performed. Some of these efforts were performed during preparations for major program milestone reviews, and others were performed as independent efforts, the results of which were summarized at subsequent milestone reviews. Some of the more significant of these efforts are described in the following paragraphs.

a. Major Program Design and Certification Reviews. System safety milestone reviews were an integral part of each major Skylab Program review. Each of the basic project and overall program milestone reviews, such as the PDR, CDR, and DCR, included (1) safety as a part of the various system and subsystem reviews and (2) separate safety review segments in the individual module and overall cluster systems reviews.

System safety representatives from SL-TQ, including integration contractor system safety personnel, participated in all design reviews in addition to the safety representatives from the respective MSFC Skylab project offices, contractor, and MSFC S&E organizations. The primary method for identifying and resolving potential problems was through the submittal of RIDs. The RID system, which included a formal review and disposition by special teams and final approval by the project and program manager, was a supplement to the overall configuration management system. The process of bringing potential problems to the attention of management was primarily used through the CDR phase of the program. At the CDR alone, over 500 safety-related RIDs were submitted for the major modules and experiments. The various safety offices submitted 140 of these. At the time of the DCR, all CDR RIDs were closed.

(1) Supplemental Reviews. The basic milestone reviews and certifications have become more or less standard procedure in all large NASA programs. In addition, a number of supplemental reviews progressively performed throughout the Skylab program treated system safety as an integral element. Examples of these supplemental reviews (and inspections) are as follows:

- Skylab Cluster Systems Review
- Skylab Subsystems Reviews (includes NASA Headquarters Baseline Reviews)
- Progressive Crew Station Reviews (module level series)
- Crew Compartment Storage Reviews
- Cluster Systems/Operations Compatibility Review
- Configuration Inspections
- Crew Compartment Fit and Function (reviews, tests, and demonstrations).

(2) Special Reviews and Assessments. A number of special reviews were conducted throughout the program that increased confidence in the safety of Skylab design and operations. The reviews are as follows:

(a) Ordnance Systems and Critical Mechanisms Review. The review was initiated by an MSFC Director request that an intensive review be performed of critical mechanical Skylab items and all ordnance systems. An interdisciplinary team was established, co-chaired by SL-TQ and SL-EI, which included representatives from various S&E organizations. The broad collective background of this team included mechanical, electrical, ordnance, propulsion, I&C, testing, quality engineering, and system safety disciplines. A detailed design and hardware review was performed that included such items as (1) the AM discone antenna deployment, (2) the ATM DA, (3) ATM and OWS SAS, (4) ATM launch locks and aperture doors, (5) OWS waste tank vents, radiator shield, trash airlock, and SALs, and (6) the MDA S190 window cover mechanism and MDA hatch assembly. Approximately 50 recommendations for changes were made affecting hardware, procedures, tests, and re-verification of conclusions derived from analyses and tests. In addition, over 10 requirements were initiated for the performance of new analyses.

(b) Engineering Walkaround Inspections. An inspection team consisting of senior management representatives from both MSFC and JSC was established. Team representatives were included from engineering, materials, quality, and safety organizations from both Centers. The MSFC co-chairman was SL-TQ. The purpose of these inspections was to identify potential problems and obvious deficiencies (systems were not functioned). Primary recommendations were in areas of improved housekeeping and control of nonflight items.

(c) Aerospace Safety Advisory Panel Reviews. A series of independent reviews were performed at major contractor facilities and NASA Centers. These reviews encompassed all aspects of management methods, technical requirements, analytical efforts, and their application to design and operations relative to personnel and equipment safety and the achievement of primary mission objectives.

(d) Skylab Activation Sequence/Critical Mechanisms Review. The effort was performed to (1) assess the Skylab activation sequence (SL-1) and associated critical functions and mechanisms to ensure that proper attention had been applied to areas of design, verification, and operations, and (2) penetrate potentially delinquent areas. Criticality I and II mechanisms that were activated subsequent to the initial activation phase (SL-1) were also included. The effort was primarily performed by MSFC S&E organizations with integration contractor support assigned by SL-EI (electrical and sneak circuit analysis personnel) and by SL-TQ (system safety personnel). Potential problem areas were coordinated with hardware contractors for supporting analysis or corrective actions. Progressive status and results were provided

to SL-EI and SL-TQ by S&E review team co-chairman. The review of activation sequence functions included power paths, pyrotechnic paths, signal paths (commands), redundancy, timing and sequencing, interlocks, backup modes (contingency analysis), and KSC verification (systems.) The review of critical mechanisms included the reverification of (1) materials surveys and assessments, (2) vibration analysis, (3) dynamic loads, (4) strength analysis, (5) qualification tests, assessments, and results including functional, environmental, life cycle, vendor changes, and process specification changes, and (6) KSC verification. Continuous coordination between the activation sequence review team and the critical mechanisms review team was provided. This review resulted in a number of corrective actions for items considered to be risks.

In the area of critical mechanisms alone, 62 assemblies were re-viewed in each of 11 categories, resulting in 682 individual assessments covering 22 subsystems. Most categories were reviewed by more than one S&E organization. A supplemental visual inspection was made using the one-g trainer at JSC. Fifteen areas required further investigation, eight of which required special emphasis and additional analysis.

(e) Skylab Activation Sequence Hardware Integrity Review. The review was initiated subsequent to the activation sequence/critical mechanisms review. The review involved all MSFC and major contractor organizations responsible for the design and development of Skylab hardware (SL-1). The purpose was to extensively re-examine all activation sequence hardware by means of an analysis of the hardware qualification requirements; a reassessment of qualification test results; a review of hardware changes subsequent to qualification; a reassessment of hardware failures and nonconformances experienced since qualification; a comparison of the configuration and building processes of both the qualification and flight hardware; and an analysis of the quality controls and tests performed on the hardware. The review covered all hardware associated with the 53 Skylab activation sequence functions.

Before completion of this review, an "MSFC Blue Ribbon Audit Committee" was established by the MSFC Director. The committee, consisting of members at the S&E Laboratory directory level, the MSFC Director of Safety and Awareness, and representatives from SL-EI and SL-TQ, was established to ensure that the integrity of all hardware related to Skylab activation sequences had been revalidated by the major contractors and MSFC. Sample hardware was selected from the 53 activation sequences for examination in depth. The basis for selection of each sample was that it be representative of other electrical, structural, and mechanical hardware in the various activation sequences; representative of prime contractor, subcontractor, and government furnished hardware; representative of different Skylab environments; representative of hardware qualified by tests, similarity, and analysis; representative of hardware from previous programs that were used on Skylab as well as new hardware specifically designed for Skylab and representative of hardware within all criticality categories. Typical documents reviewed in depth for hardware sampled included (1) FMEA and CIL, (2) fabrication and assembly shop orders, (3)

ders, (4) waivers and deviations, (5) discrepancy re-
ure reports, (6) welding specification, (7) configura-
ol manuals, (8) wiring and cabling specifications and
(9) qualification and acceptance test data, including
and test reports. A number of potential problems requir-
anges were identified by MSFC and contractors as a result
Others were identified and corrected as a result of
s and tests subsequent to the audit.

ylab System Safety Checklist Program. Concurrent with,
to, all activities previously described in which system
l were directly or indirectly involved, a wide variety
em safety studies were performed. These studies were
ll three categories identified in V.C.1, and were per-
he scope of overall program planning, definition, status,
efforts provided by SL-TQ. The system safety policy,
s, mangement, and implementation approach previously
ted in effective communications, total program involve-
red visibility to system safety personnel of problems
affected the basic system safety objectives. Special
performed for the purpose of identifying solutions to
tions, had a significant influence on overall manage-
One of these studies resulted in the development and
f the Skylab System Safety Checklist Program.

Basic System Safety Checklist Program Objectives. As
iminary planning activities and the review of documenta-
us programs, studies were conducted to develop improved
rea of hazard identification and corrective action.
line documents, hazard catalogs, and accident-incident
een developed and are all valuable indicators of past
wever, a review of this documented experience during
am clearly indicates that certain types of hazards
unsafe failures, accidents, and incidents repeatedly
ram. Even with increased emphasis on the performance
Logic Anglyses, Sneak Circuit Analyses, and many other
analysis, a remaining management concern existed in the
e control of proven accident causes. Thus, an improved
: application of safety-related experience was sought
hermore, as a result of action items from the Skylab
, a safety review of the entire Skylab Cluster and an
adequacy of protection for flight systems from GSE
ed as part of a Systems/Operations Compatibility Review.

es of the checklist technique developed were as follows:

ermine the actual status of Skylab design features or
ional conditions that could result in systems failure,
ent damage, or personnel injury.

- To establish a systematic hazard identification and assessment program to supplement existing analytical efforts such as FMEAs, sneak circuit analyses, and hazard analyses.
- To develop an approach to assess Skylab designs and operational conditions, using a broad combination of safety-related experience from the aerospace industry as criteria.
- To provide a method to ensure effective implementation and visibility to management of results.

(2) Checklist Development. Four System Safety Checklists were developed using a broad combination of documents such as those in Table V.C-3.

Table V.C-3. Typical Source Data for Checklist Development

<u>SKYLAB SYSTEM SAFETY CHECKLIST PROGRAM</u>	
Manned Space Programs Accident/Incident Summaries	NASA, Dir of Safety, March 1970
System Safety Accident/Incident Summary	NAR, Space Div. July 1967
Air Force Eastern Test Range Safety Manual, Volume I	AFETRM 127-1, January 1, 1969
Minutes, System Safety Network Technical Interchange Meetings	
Space Flight Hazards Catalog	MSC 00134, Rev A. January 1970
Management Manual Technical Information Bulletins	MSC-M8081. January 1970
Space Flight Hardware Accident Experience Report	MSFC. October 14, 1966
Apollo 14 Safety Assessment	MSC-SN-1-174-10. December 2, 1970
Air Force Systems Command Design Handbook, Series 1-0	DH 1-6. July 20, 1968 Rev. July 20, 1970
Report of Apollo 204 Review Board ... All Appendixes	April 5, 1967
Report of Apollo 13 Review Board ... All Appendixes	June 16, 1970
Manned Spacecraft Criteria and Standards	MSCM 8080, April 26, 1971

Accident-incident data were converted to positive design criteria statements and specifically tailored to assess the hardware systems and equipment indicated by the following general titles:

- Ground Support Equipment Design (SA-003-001-2H, July 1971)
- Flight Systems Design (SA-003-002-2H, November 1971)
- Experiment Systems Design (SA-003-002-2H, November 1971)
- Experiment Ground Support Equipment Design (SA-003-004-2H, November 1971)

(3) Implementation Approach. The approach selected for checklist implementation was to allow Skylab design organizations to assess the hardware for which they were responsible at the time the checklist was issued. This approach permitted the most rapid and accurate safety assessment of the Skylab hardware by using the personnel most knowledgeable of the design details - the design engineers. In addition, a system for receipt, review, evaluation, followup with design organizations, statusing, tracking of potential problems, and actions taken was developed concurrently with checklist development and issuance.

The checklist format, as shown in Figure V.C-3 with sample criteria statements applicable to GSE design, was unique in both the manner in which it was written and the manner in which it was intended to be used. The intent was to provide actual status of design features. Therefore, such common terms as "critical", "high pressure", "low pressure", "high voltage", and "shall be avoided" were not used. Words of this type could have led to ambiguity and might have been subject to differences of opinion. The format was designed to accommodate a specific procedure for completion and standardized processing of the checklists at MSFC. The procedure was developed to attain the stated checklist program objectives. The basic procedure for completion and return is outlined as follows:

- Checklists were intended for use by the lowest organizational design element having responsibility for an end item or subsystem.
- Columns were to be marked based on actual conditions of design, regardless of what may have been required in the design specification.
- "Noncompliance" or "Not Applicable" responses required a statement on a supplemental status form describing and justifying the existing conditions, or describing the alternative method by which the intent of the stated criterion had been met. The checklist statements were meant to be taken literally, i.e., compliance with the intent was not cause for marking the compliance column.
- Completed checklists were to be signed and returned to the issuing organization for review, evaluation, and statusing.

(4) Ground Rules for Program Implementation. Ground rules for contractual action control, approval cycles, release procedures, tracking of problem-action summaries, etc., were as follows:

- Checklists would neither impose requirements on the designs nor, in themselves, authorize or recommend design changes.
- Checklists would be released by appropriate project offices.
- Upon receipt of returned checklists by project offices, copies would be submitted to SL-TQ for review, evaluation, and status-ing.
- Processing by SL-TQ would include the preparation of problem-action summaries that would be submitted to appropriate management for further investigation or corrective action. A special task team was established by the Skylab Program Office to assist in uniform problem verification, followup with design organizations, and to recommend or initiate corrective actions as appropriate.
- Problem-action summaries would be tracked until closed by MSFC or contractor action. In other words, tracked until a design change was approved and incorporated or the disposition and rationale for risk acceptance was approved by program management.
- Constraint inputs to plans, procedures, and operations (flight and ground, to include tests, handling, transportation and storage) would be developed based on hazards identified and residual risks that management deemed acceptable.

(5) Benefits to Skylab. This do-it-yourself checklist technique and the broad-based systematic application of checklists, in combination with the evaluation and corrective action system, resulted in the following:

(a) Demonstration that if experience retention information is brought to the attention of the designer in a direct manner, he will apply it. Oversights in new designs and in converting equipment from previous programs to new uses on Skylab were identified and corrected. Many of these actions were initiated by the responsible design groups during checklist completion before return of the checklist to MSFC. "Noncompliance" columns were marked and the actions that were in process to correct deficiencies were stated in the supplemental rationale.

(b) Provided a method for coordinating the efforts of many Government and contractor organizations from a systems safety point of view. Detailed reviews of managerial controls, processes, and operating procedures resulted from questions brought out by evaluation efforts. The reviews considered such factors as controls to prevent installation of components in reverse, controls to ensure application of proper torque values, verification of pressure regulator and flow control device settings, verification of cleanliness levels of GSE before use with flight hardware, and inspection of connectors for bent pins, foreign objects, or contamination before mating.

(c) Extended the capability of a small group of system safety specialists to permit a program-wide safety assessment through engineering organizations responsible for hardware development. Names and department numbers of individual engineers who had completed each checklist section were submitted to MSFC with each checklist. Rapid response was provided by telephone to questions arising during the evaluation process. Copies of detailed drawings or procedures were submitted upon request as required to process potential problem-action summaries. The use of existing design groups minimized the development and continuous maintenance (changes) of detail design schematics at the component, subassembly, or subsystem level by the system safety evaluation group. Design changes occurring after initial checklist submittal were reviewed against checklist criteria by the design group responsible for the change. Supplemental status sheets were submitted to the safety evaluation group for changed items. This supplemental status was reviewed for impact against previously baselined safety checklist status for the equipment.

(d) Provided management with visibility of results. Centralized processing of completed checklists and a coordinated corrective action system provided a focal point for overall checklist program status. Comparisons between checklists for flight and ground equipment used in combination resulted in the identification and resolution of potential hazards not recognized at the individual equipment level. Significant risks were immediately brought to the attention of the responsible design organization for confirmation and corrective action recommendations. Potential problems were resolved through CCB action. Skylab system safety checklist program status reviews were included as part of periodic MSFC Skylab Program Management Reviews. In addition, checklist status was included as a special subject within Reliability and Safety portions of the DCR, both at the individual prime contractor level and at the overall Skylab level.

(6) Summary of Results. Over 600 checklists were completed. More than 80 actions were taken to eliminate or significantly reduce the potential for failure or accident. Examples of actions taken are as follows:

(a) A single failure could have resulted in multiple loss of detection capability in orbit. The 3.6 Amp fuses in 12 separate Fire Sensor Control Panels associated with 22 separate sensors were changed to 1.0 Amp fuses. The characteristics of the 3.6 Amp fuses were essentially the same as the "trip" characteristics of the circuit breaker for all fire sensors associated with a particular bus. Therefore, if a short circuit or overload condition were to develop a single sensor or its associated wiring, it would have been possible to lose all fire sensors powered from the affected bus (last statement, Figure V.C-3). The action was initiated by the prime contractor, who was responsible for the Skylab C&W system, on detection of a deficiency during initial checklist completion. The action was implemented by all three prime contractors responsible for the three modules that constituted the habitable areas of the Skylab.

(b) A single failure could have resulted in a launch delay because of flight or ground hardware damage. Three separate relief valves were changed within a console to provide relief flow capacity greater than that of the upstream pressure regulators in the event of regulator failure. The console incorporated parallel multistage pressure regulation to ensure reliability. A change to increase console operating pressure and flow rate subsequent to the original design resulted in an oversight to reverify the orifice size of the relief valves. The action to correct this condition was initiated during the evaluation process. A retest of the new configuration was performed on a prototype console (qualification unit) under simulated failure conditions. The modification was then made to the console that was used during flight hardware tests at KSC.

A System Safety Checklist, Skylab Program Report, TMX-64850, has since been developed and issued by the MSFC Skylab Program Office for the benefit of future programs. The single volume document contains over 500 criteria statements applicable to flight systems, experiments, other payloads, associated GSE, and facility support systems. The document contains updated criteria statements from all four Skylab checklists and reflects additional experience gained during the Skylab program. The document contains suggestions for progressive application of checklist criteria beginning with the preliminary development of design requirements and specifications.

D. Quality Assurance Program

1. Objectives and Methodology. Provision for quality control of Skylab hardware, from initial design through final testing and acceptance, was instituted early in the program with the establishment of a Reliability and Quality Assurance Program. Quality Assurance is a planned and systematic pattern of all actions necessary to provide adequate confidence that the end items will perform satisfactorily in actual operations. The NASA Quality Assurance program was defined and established in the "Apollo Applications Reliability and Quality Assurance Plan" (NHB 5300.5) dated May 1967, "Quality Program Provisions for Aeronautical and Space Systems Contractors" (NHB 5300.4 (1B)) dated April 1969, and "Inspection System Provisions for Suppliers of Space Materials, Parts, Components and Services," (NPC 200-3) dated April 1962. Additional quality requirements are established in the Cluster Requirements Specification (RS003M00003). The quality requirements of the above listed documents were imposed on the various hardware contractors through the Contract Statements of Work. Quality provisions were also included in the Contract End Item (CEI) specification documents for each contractor.

Subject to the above listed documents, each contractor prepared a quality plan detailing the operation of the respective Quality Programs. The objectives of the contractor plans are:

- Development and manufacture, from the initial phase to delivery, of missile and space systems that meet the quality requirements of NASA (and the contractor).
- Timely emphasis and planning toward the solution of potential problem areas related to quality in all program activity areas.
- Documented provisions for the accurate evaluation and evidence of status and progress in accomplishing program quality goals.

MSFC had the prerogative of disapproving these plans, partially or entirely, if in its implementation it failed to achieve the desired objective of the contract. Additionally, the contractors were subject to continuous evaluation, review, and inspection by MSFC or its designated representatives.

2. Implementation and Management Control.

a. Design and Development

(1) Drawing and Specification Review. In early program phases, Quality Assurance manifested itself in the area of documentation. As design, development, procurement, and specification documents became available for release, they were reviewed to ensure adequate requirements

for determining and controlling product quality. Drawing review included consideration of the following quality criteria:

- Standardization of drafting and design practices relative to parts, identification, characteristic definition, tolerances, and test requirements;
- Application of qualified and approved/preferred parts;
- Adequate dimensioning for manufacture and inspection;
- Proper surface finish;
- Proper specification callouts;
- Adequate general notations to permit Manufacturing and Reliability Assurance to fabricate and inspect all aspects of the design pertinent to form, fit, and function;
- Standard processing, manufacturing, and tooling callouts (tooling holes) as applicable;
- Adherence to standard design in tube bend radii, minimum machine radii, hole tolerances, hole runout allowance, sheet metal bend radii, and other standard contractor drafting and manufacturing practices;
- Adequate identification of article;
- Reference to applicable technical documents, including test requirement callout;
- Acceptance parameters and conformance limits for all characteristics that influence quality, as applicable;
- Qualification test requirements in drawings released for procurement, as applicable.

(2) Test Program. As early hardware for development and qualification testing became available and testing was initiated, Quality Assurance provided support and surveillance for the tests. Primary emphasis during the testing was to ensure that instrumentation and measuring devices were within calibration time limits. For qualification testing, Quality verified the test article to be of the proper production configuration and functionally acceptable for conduct of the qualification test.

b. Traceability. Each contractor developed a Quality Assurance documentation system to provide for and control the identification of piece parts, materials, and articles to which procurements, fabrication,

inspection, test, and operating records were related and all aspects of the program which affected the quality of the product. All pertinent information relative to materials, processes, test data, and performance were documented and verified on the completed planning paper. It was required that flight and backup hardware components be traceable to the "lot" level. Quality data considered essential to the program or developed by the contractor as objective evidence of compliance to quality requirements were made available to the NASA representative for review as required.

c. Procurement Control. The Quality organization had primary responsibility for ensuring the quality of procured articles. Procurement quality activities were performed to assure that:

- Suitable suppliers were selected.
- The quality of incoming materials met contractual, engineering and program specifications.
- Procurement documents contained Quality and Reliability requirements.
- Materials were controlled during the manufacturing process by ensuring that they were properly identified, handled, and adequate records of test and inspections performed were available.
- The supplier met the appropriate requirements.

(1) Source Selection. The selection of procurement sources was based upon the supplier's historical records or survey reports. Reliability Assurance reviewed and provided comments on the adequacy of all procurement sources. Selection procedures included consideration of the following:

- Does supplier have a record of supplying high quality articles of the type being procured?
- Surveys and audits were conducted on the supplier's facilities and Quality Control systems for the capability of supplying items that meet all quality requirements. Results of these surveys and audits were documented and made available to MSFC or its designated representative upon request.
- Review and approval of written supplier quality plans.

Additionally, Quality verified that the necessary failure history reviews were performed before purchase order approval to ensure that parts required by design did not exhibit unsatisfactory trends. As the procurement phase continued, supplier performance trends were used as a basis for disapproval where unsatisfactory conditions occurred.

(2) Procurement Documentation. Quality reviewed purchase orders before contract commitment to ensure that quality standards and all pertinent requirements, including reliability specifications, were documented in the contract with the supplier.

Drawings and specifications pertinent to the procurement, including supplier drawings that formed part of the basic contractor drawings/specification, were reviewed in accordance with criteria established by the contractor quality plan.

Purchase orders were submitted to the Resident Government Quality Representative for review and comment.

Purchase orders were reviewed to verify the inclusion of the following information, as applicable:

- Basic technical requirements;
- Intended application;
- Detailed Quality requirements;
- Change control procedures;
- Raw material test analysis;
- Preservation, packaging, packing and shipping;
- Age control and life limiting requirements;
- Identification requirements;
- Inspection and test requirements;
- Handling of inspection and test records;
- Resubmission of rejected articles;
- Government Source Inspection (GSI) requirements;
- Source inspection; and
- Data package requirements.

(3) Receiving Inspection. Upon receipt of procured articles in the receiving inspection area, evidence of supplier inspection in accordance with terms of the purchase order, and source control requirements were satisfied before initial acceptance was made. Contingent on results of the initial inspection, articles were routed for completion of the receiving inspection process in accordance with a Receiving Acceptance Procedure. This included, but was not necessarily

limited to, a physical examination, identification, and tests; disassembly was accomplished as appropriate. Articles subject to age deterioration were examined for proper marking and verified to have sufficient remaining life. Records were maintained and updated if life or cycle use occurred during receiving inspection activities.

When necessary, chemical analysis and physical tests to verify material quality were conducted on test specimens submitted with purchased articles. Verification of raw materials conformance to specification was periodically conducted on samples randomly selected to determine accuracy of supplier test reports.

(4) Government Furnished Equipment (GFE). The Contractor was responsible for receiving GFE and reviewing data and documentation to determine that the hardware was acceptable for the intended Contractor use. Quality reviewed inspection records and hardware to determine if shortages, damage, or unacceptable conditions existed. Functional testing was not required. The Contractor was to notify the customer representative of any GFE received that was unsuitable for its intended use.

Contractor maintained records of GFE that included the identification of the property, dates, types, and results of Contractor inspections, and other significant events.

d. Fabrication Control

(1) Cleanliness Control. Procedures were established to control contamination levels during required stages of fabrication, assembly, test, and packaging operations. Quality monitored all environmentally controlled work areas, and inspected all controlled articles and commodities for compliance with the CEI specification cleanliness requirements.

(2) Material Control. Materials were stored in controlled storage areas. When material was issued against a manufacturing process, Quality would verify the material issued by stamping the material block of the process plan. Quality also verified that the issued material was identified by material type and lot number. The issued material would be stamped by Quality, and the identification and lot information entered in the process plan. Nonconforming material was identified and withheld from production flow.

Materials subject to limited shelf life were identified and controlled to prevent use beyond the life expiration date. Time-cycle data was accumulated on sensitive equipment to assure that adequate life remained for subsequent end usage. Log books reflected remaining useful life of all limited life and time/cycle sensitive articles.

(3) Process Control. Manufacturing processes were reviewed and approved by Quality before use. Control included initial facility approval and operational adherence to the intent of the design

and manufacturing requirements, as well as the stated requirements of applicable specifications. Inspection personnel ensured compliance with process requirements, that the process had been approved by Quality, and that no unauthorized or outdated processes were in use.

(4) Fabrication Inspection. Inspection monitored fabrication operations, inspected all completed items, and performed in-process inspections as required to assure the proper level of workmanship and quality of the end item. The results of these inspections were documented and the parts identified to provide objective evidence of Quality acceptance.

Discrepancies found during fabrication or before acceptance were documented and the discrepant item returned to Manufacturing for rework to drawing. Items that could not be reworked to drawing were identified "withheld" and processed to Material Review Board (MRB).

e. Inspection and Test

(1) Planning. The control of Contractor-fabricated articles consisted of a planned program of inspections and reviews conducted to ensure compliance to contract requirements during all phases of contract performance. These reviews were conducted by Quality and encompassed all the technical documents used to fabricate and test the end items. In addition to establishing inspection requirements, these reviews provided assurance that the items could be built, inspected and tested, and that the Engineering and Contract requirements would be met.

All inspections performed on the end item, its components, or raw materials, were planned and documented to provide a complete record of the inspection, by whom, and the date it was performed. The planning assured that inspections were performed in a logical sequence, at convenient points within the fabrication and test cycle, and allowed these operations to proceed consistent with good control practices.

(2) Operation. Installations and assemblies were fabricated in accordance with Quality-approved Assembly Process Plans. Before installing components, mounting holes, and bracket dimensions were inspected for correct dimensions and locations per drawings. Quality verified acceptable completion of component inspection and functional test before installation of components and equipment into the carrier. All items in the process plan requiring quality buy-off had to be accomplished before proceeding to end item testing. To the extent practicable, each fabrication and assembly inspection and test operation was traceable to the individual responsible for its accomplishment.

Quality controlled the validation of official test procedures, verified proper procedure configuration, and maintained status of all procedures, completed, in work, or unaccomplished. Quality reviewed

records and witnessed acceptance tests. All variations, anomalies, or failures were documented in the procedure history sheet.

At the completion of end item testing, and before pack and ship operations, a final inspection of the completed articles was conducted by Quality. Results of final inspection were documented in process plans and in quality check sheets prepared by Quality to assure that all inspection requirements were met. Quality would review equipment log books for completeness and accuracy. A review of limited life components data would be performed to assure that remaining life was sufficient to accomplish the mission. Upon completion of final inspection and resolution of all open items, Quality would initiate COFW endorsement to indicate that all Quality requirements have been satisfied, and presented the COFW to NASA. Integrity control was maintained on accepted articles. Any repairs, modification, or replacements accomplished after final inspection and test, necessitated reinspection and retest to the extent determined necessary by the Contractor, subject to the approval of NASA.

Quality conducted Incremental Summary Reviews (ISR) for the equipment at fabrication milestones as mutually agreed to by the Contractor and NASA. ISR data for these fabrication milestones was prepared by Quality for resident NASA review and approval. The COFW was presented to resident NASA for sign-off at these milestones, before transmittal to NASA MSFC.

(3) Documentation. Quality maintained records of inspections and tests performed throughout the entire procurement, fabrication, and assembly processes. The records provided evidence that required inspections and tests had been performed on raw materials, procured parts, fabricated details, and completed articles. All quality data was accumulated and maintained in retention and included vendor data, laboratory analyses, calibration records, nonconformance history, receiving inspection reports, fabrication, and assembly records.

Historical logs were prepared and maintained for all major airborne components, subsystems, and systems. Each log, identified to the equipment to which it pertained, was maintained in chronological order and accounted for all periods of time and any movements of the item, thereby, documenting its history. Historical logs consisted of data derived from component data packages, certification logs, and other test and inspection data necessary to comply with quality and contract requirements.

The contractors prepared an Acceptance Data Package for each contract end item of hardware in accordance with the Configuration Management Plan. This package was presented to NASA MSFC or its delegated representative at the time of acceptance.

f. Nonconforming Material. Quality Assurance was responsible for detection and reporting of nonconforming materials. Upon detection,

all nonconforming material was removed promptly from the manufacturing system and compounded, if practical, for disposition and for completion of the nonconformance report.

(1) Material Review Board (MRB). The MRB was a formal contractor/Government Board established to determine the disposition of minor nonconforming material and recommend disposition of major nonconforming material.

Items that could not be acted upon routinely were presented to the MRB for disposition. The MRB consisted of an authorized Quality representative, an authorized representative of the Engineering organization, and a customer representative.

The Contractor representatives were specifically authorized to act on material covered by this contract. Contractor personnel were certified to participate in board activities.

The Contractor MRB members coordinated and recommended disposition before submittal to the customer representative. The MRB disposition required the concurrence of all three members. Disposition could be one of the following:

- Use "as is";
- Repair-Nonconforming material that could be made acceptable by repair;
- Scrap-When nonconforming material could not be used "as is" nor satisfactorily repaired.

When the MRB disposition was "repair" and a nonconformance existed after completion of the repair, that could effect safety, reliability, durability, performance, interchangeability, weight, or the basic objectives of the contract, the Contractor submitted a written request to the contracting officer for approval of that condition.

(2) Identification and Routine Disposition. Hardware determined to be nonconforming was identified and segregated, the initial identification being made by Quality personnel. A Withheld tag was attached to the discrepant item to denote pending disposition as required by procedure. Reacceptance in the form of stamp application occurred when the disposition was completely satisfied, including 1 retest and pertinent data review.

Disposition of defective articles could be made without MRB action. The dispositions that could be given follow.

- Complete to Drawing - Items that were incomplete or could be restored to the original configuration were corrected in accordance with drawings and specifications;

- Recommend Scrap, Refer to Material Review - Items obviously unfit for use or uneconomical to repair;
- Refer to Materials Review Board - If other than above applies.

"Complete to Drawing" disposition could be authorized only when written procedures defined the rework involved. Any material undergoing work would be completely reinspected to ensure that the material meets the required drawings and specifications. Detail rework manufacturing plans were approved by the Quality representative of the MRB before issuance of work folder.

(3) Corrective Action. Action had to be taken to correct conditions that contributed to, and were inherent in, nonconformance (including flight readiness action and recurrence control action). Failure reports were considered open by the Contractor until corrective action was implemented. In all cases a positive statement of corrective action or rationale as to why action was not required, was necessary to close out a failure report.

Quality personnel classified failures and notified the resident Government representative of all category No. 1, and IS, 2A, 2B and 3 failures within 24 hours. Quality personnel prepared compilation of problem history sheets into a Corrective Action Problem Summary, which was submitted as part of the Quality Status Report to the Customer. Subsequently, a revised sheet would be included for problems where the status had changed. The final history sheet on an individual problem defined the closure action taken.

g. Preservation, Packaging, Handling, Storage and Shipping. Design and performance criteria for the preservation, packaging, packing, and transportation by the Contractor for the delivery of equipment, was developed to achieve the following objectives:

- Efficient, economical protection from damage during handling, storage and shipment;
- Prevention of product deterioration;
- Proper identification and marking ensuring efficient receipt, storage, inventory, and issuance;
- Uniform protection of similar items;
- Economy by the use of package and containers of minimum weight and volume;
- Maintenance of required environments and provisions of indications for critical environment where necessary.

Quality Assurance reviewed the instructions for these items to ensure incorporation of quality requirements. This included providing, as necessary, inspection instructions in the manufacturing work authorities.

(1) Preservation and Packaging. Packaging drawings and processing instructions were prepared and released for use by Manufacturing in establishing preservation and packaging methods. The preservation and packaging methods conformed to all applicable requirements. Packaging data were developed for each item shipped in accordance with the packaging plans and process instructions. Quality Assurance accomplished inspection of the unit, intermediate and final packaging, and crating. When maintenance of specific internal or external environments were necessary, these were included in the packaging and necessary special instructions provided on the exterior of the package for monitoring by Quality Assurance.

(2) Handling and Storage. Special carts, containers, and transportation vehicles to be used were prescribed in handling and storage process instructions to prevent damage due to handling during fabrication and processing.

(3) Shipping. Quality Assurance inspected and controlled articles shipped from the Contractor to assure that:

- Articles had been subjected to, and satisfactorily passed, applicable inspections and tests. Emphasis was given to the physical segregation of conforming articles from those awaiting test results or final disposition.
- Articles were complete and fully assembled as required, or necessary waivers had been obtained.
- Articles had been preserved and packaged in accordance with applicable procedures and process instructions.
- Packaged articles were identified and marked in accordance with applicable procedures and process instructions.
- In the absence of packing and marking requirements in the contract or subcontract, packing and marking of articles complied with Interstate Commerce Commission rules and regulations and commercial practice. The articles were packaged to ensure safe arrival and ready identification at destination.

VI. Bibliography

SECTION VI. BIBLIOGRAPHY

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Checkout System ESE Logistics Plan

138.C0.4

Logistics Spares List

APPROVAL

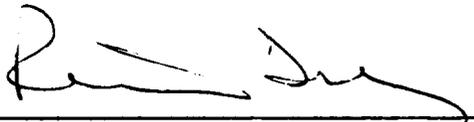
MSFC SKYLAB PROGRAM ENGINEERING
AND INTEGRATION

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.



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